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Nonwater Quality Impacts of Closed-Cycle Cooling Systems and the Interaction of Stack Gas and Cooling Tower Plumes

Cameron Engineers, Inc, Denver, CO

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Nonwater Quality Impacts of Closed-Cycle Cooling Systems and the Interaction of Stack Gas and Cooling Tower Plumes

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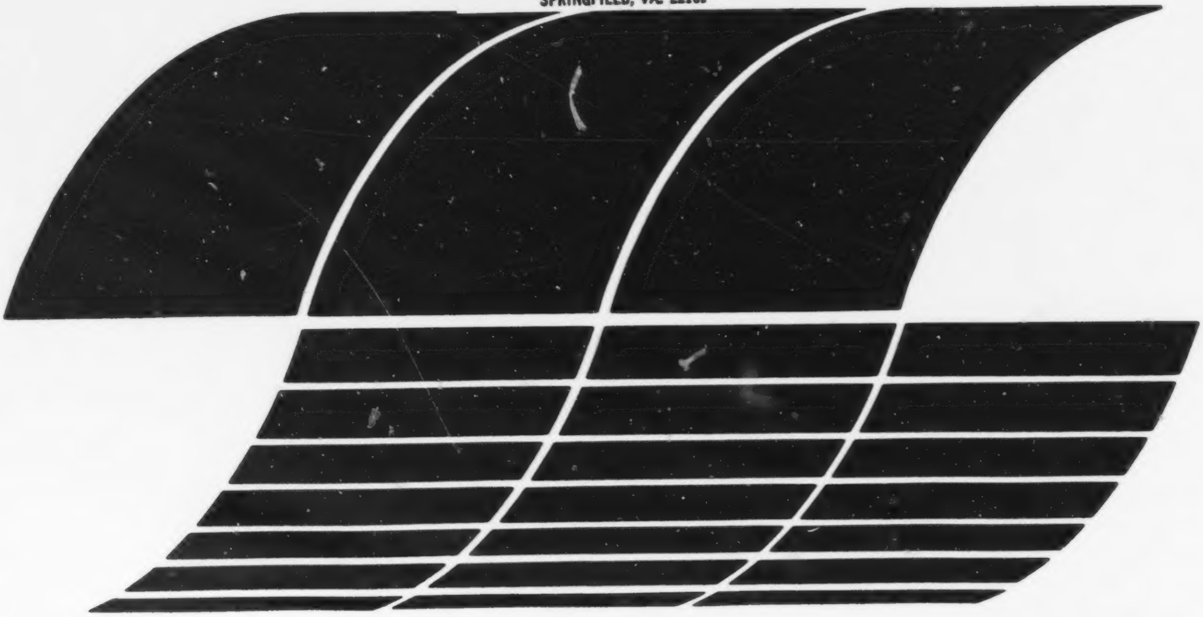

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ABSTRACT

This report presents the results of a literature survey on the non-water quality impacts of closed cycle cooling systems and the interaction of power plant stack gas and cooling tower plumes. The purpose of this report, prepared for the Environmental Protection Agency (EPA) by United Engineers & Constructors, Inc. (UE&C), is to document the state-of-the-art concerning the impact of drift from evaporative cooling towers and the interaction of cooling tower plumes with stack gases from fossil-fueled steam electric generating stations.

Cooling tower plumes and stack plumes are treated as separate topics, followed by a discussion of plume-stack gas interactions. For cooling tower plumes, plume types, behavior, salt drift generation and deposition, and inadvertent weather modifications are reviewed. Special emphasis is placed on meteorological conditions which enhance deposition, icing and fogging, and cloud formation.

The cooling tower-stack gas interaction discussion emphasizes categories and mechanisms of interactions, acid precipitation enhancement, case studies of operating power plants, and practices proposed to reduce or minimize cooling tower/stack plume interactions.

The adverse biological impacts of acid precipitation, cooling tower drift, and icing and fogging on the biota are considered. The effects of acid precipitation on soil, soil biota, vegetation and aquatic biota, including vegetation, planktonic and benthic organisms, and fish are discussed with reference to levels causing harm or injury. The nature of cooling tower drift is examined for areas important to environmental impact assessment. These include: atmospheric and cooling tower salt loading, cumulative effects of both, and salt tolerances of plants and animals. Emphasis is placed on threshold concentrations at which the biota is affected by drift deposition and the distances from the cooling tower where toxic levels are attained.

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SECTION 1

INTRODUCTION

The objective of this study under contract from the Environmental Protection Agency was to collect, analyze and correlate available information on: a) the impact of drift from evaporative cooling towers, especially saltwater towers, and b) the interaction of cooling tower vapor plumes with stack gases from fossil-fueled steam-electric generating station.

The results reflect an intense ten man-month effort performed in a three man-month period (October 1977-January 1978) to complete a thorough state-of-the-art investigation. Due to the limitation of time and funding, omission of some of the available data is possible.

The information thus collected and correlated forms a part of an overall effort sponsored by EPA and is intended to provide background information for the revision of the water pollution regulations for steam-electric power plants.

Five tasks were performed to satisfy the requirements of this project. For each task, several subtasks were carried out to survey and select literature sources, to review and analyze the data collected, and to tabulate the relevant information.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

1. The limited amount of field data on the quality and impact of drift from saltwater cooling towers is insufficient to make a firm, general conclusion on their drift effects.

2. Predictions of drift deposition by various models give wide variations. A current evaluation by Argonne National Laboratories of 12 different computer models used to predict drift deposition (including the program used by NRC in the preparation of Environmental Impact Statements) indicates that the predicted results may vary from 2 to 10 times that measured during tests performed at the Chalk Point Power Station.

3. Cooling tower drift and deposition from natural draft towers apparently do not increase ambient salt loading to the extent that a significant impact has been observed. Field data from the operational Chalk Point and B. L. England Stations indicate that although drift and its deposition from cooling towers may be significant within the immediate environs of the station, its impact beyond 1 kilometer (km) may be inseparable from the natural salt loading characteristic of those regions.

4. Insufficient and inconclusive data exist on the degree of salt injury to the biota caused by cooling tower drift. The only existing field data obtained from the Chalk Point and Turkey Point towers indicated that acute drift effects on vegetation may occur in the immediate environs of the cooling tower, perhaps up to several hundred meters downwind. Chronic effects of long-term operation of cooling towers are not known.

5. Enhancement or reduction of acid precipitation or deposition (a local or regional environmental problem) by wet cooling tower and stack plume interactions has neither been established nor demonstrated in the field.

6. Plume interaction impacts on the biota are not definable at this time. Interaction between evaporative cooling tower plumes and stack gases from fossil-fueled steam-electric generating stations has not been conclusively shown to enhance or abate acid deposition/precipitation.

7. Based upon field observations, fogging and icing from natural draft cooling towers are not environmental problems. At most, only a few millimeters of ice have been observed to accumulate on surrounding structures. Fogging from natural draft cooling towers has not been observed under a variety of meteorological conditions.

   For mechanical draft cooling towers, fogging and icing have been observed. Because of more severe downwash effects and lower tower heights, the buoyant plume has been observed to intersect the ground, usually within a few hundred meters. The tower design significantly affects the probability that the plume will intersect the ground. Plumes from line mechanical draft towers are much more likely to impact the ground than plumes from round mechanical or fan-assisted natural draft towers. Rectangular mechanical draft cooling towers have been observed to cause plume and ground intersection about 10 percent of the time. Severe icing has been observed covering local structures and vegetation with 0.25 in. of ice to a distance of about 250 m.

8. Modification of weather, such as precipitation and cloud enhancement, by wet cooling towers has been insignificant. In the few documented cases of weather modification, the average effects caused by cooling towers have generally been minimal. Nearly all studies indicate that precipitation and cloud enhancement for any single sector downwind from a tower are increased by only a few percent. One study currently underway at Oak Ridge National Laboratories predicts that heat rejection from a large cooling tower complex (3000 MWe) will cause an apparent increase of 15 percent in the amount of precipitation in the direction of the prevailing wind.

2.2 RECOMMENDATIONS

1. Comprehensive pre- and post-operational studies of cooling tower drift and deposition using standardized measuring techniques are recommended.

2. Extensive field investigation should be undertaken in the following areas: a) dose/response relationship of salt drift, b) cooling tower drift impact on local biota under the conditions in which flora would normally be exposed, emphasizing long-term cumulative effects.

3. Dose-response data from one species should not be applied to other species for which no experimental toxicity data exist.

4. Extrapolation of laboratory data to natural situations of operating cooling towers should be undertaken with caution until existing saltwater cooling towers are well into the post-operational stage and a sufficient data base is available.

5. Both theoretical investigation and field measurements should be undertaken to determine the quantity and impact of acid precipitation deposition due to cooling tower/stack gas interaction.

2.3 DISCUSSION OF RECOMMENDATIONS

2.3.1 Salt Drift Deposition

Comprehensive pre- and post-operational studies of cooling tower drift and deposition using standardized techniques of measurement are recommended.

For example, analysis of the B. L. England data indicated that the recorded increase in deposition might not have been caused by the cooling tower but rather by different prevailing meteorological conditions observed during the post-operational period. Because only 8 of 52 data sets were considered adequate, the degree to which micro-meteorological conditions contributed to an increase in drift deposition is not known. Although the Chalk Point data indicated that operation of the cooling tower between May 1975 and April 1976 did not change ambient salt concentrations within a 9.6 km radius of the power station, long-term field studies over a period of several years are necessary to safely confirm these preliminary conclusions. In addition, inland areas where brackish underground or agricultural runoff water may be used requires particular attention, due to the dearth of information available on this topic.

2.3.2 Adverse Biological Impacts of Cooling Tower Salt Drift

Because biological impacts of power facilities generate concern and little is known about threshold concentrations at which vegetation is affected by drift deposition, this section includes a lengthy discussion of recommendations on adverse impacts of cooling tower drift. It is generally understood that operation of a saltwater or brackish water cooling tower will release measurable quantities of salt particles into the local atmosphere. The fate of these particles is not understood in real situations, although some data suggests that a portion of these particles impinge or settle on vegetation and other structures at variable distances downwind of the cooling tower. Local meteorology determines the degree and nature of salt transport.

Environmental reports indicate that operation of the cooling tower may or may not raise ambient salt levels beyond a limited, measurable distance downwind of the tower. Major ecological concern focuses on both acute effects of higher than background levels and chronic effects of long-term, low-level salt concentrations on the biota, particularly vegetation; as it has generally been argued that increased salt loading has negligible, even beneficial effects on animals.

A substantial body of literature on salt tolerances of plants and animals exists, including data on the dose-response relationship for selected species. Most studies indicate that vegetation exhibits variable sensitivity to ambient salt loading, whereas animals are generally unaffected, provided that enough drinking water is available. In assessing salt levels that are potentially harmful to vegetation, particular attention should be paid to biological factors that determine susceptibility, (including species-specific sensitivity, stage of development, and phenotype), in addition to aerosol salt concentration, rate of deposition, foliar accumulation, relative humidity, and size and degree of hydration of saline particles. All of these factors combine to produce a complex dose/response relationship, the exact nature of which is not understood in depth.

More data is needed on the dose/response relationship, particularly with regard to the effects of parameters which describe duration and repetitiveness of exposure, and the form in which salt is applied under experimental conditions. In addition, knowledge of local meteorological factors which may alter exposure patterns downwind of a cooling tower is needed to extrapolate laboratory information on salt sensitivities to real situations in the field. It is implied that salt impingement on vegetation in laboratory situations may not be representative of cooling tower salt drift impingement under operational conditions. This problem needs investigation.

A future concentrated effort should be made to be realistic in the appraisal of cooling tower effects on local biota by simulating, as best as possible, conditions under which flora would be exposed. The spectrum of local plant species that would be tested for salt drift effects should include major agricultural crops, ornamentals, and other native species. Underlying this experimental rationale is the fact that in the coastal environments where saltwater cooling towers would be situated, the vegetation has already been exposed to variable salt loads for perhaps thousands of years. Studies should emphasize the long-term cumulative effect of increased ambient salt loading on growth, reproductive yield in terms of fruit and seed production and changes in community structure (abundance and diversity). To date, these studies do not exist. Thus, it becomes impossible to assess the long-term effects of cooling tower drift on biotic communities. From the experimental data that exists at present, it may be concluded that a particular species is deleteriously affected by the aerosol conditions and its rate of deposition. An extrapolation of the existing experimental dose-response data (Table 4-17) that provides "armchair" estimates of deposition rates which may affect selected species is provided. This table provides a spectrum of susceptibility to salt in terms of sensitive and tolerant species. The following assumptions are made, regarding the use of this data:

1. Experimental salt drift treatments simulate, as closely as possible, local ambient conditions of salt impingement on vegetation.

2. Field responses of vegetation are similar to laboratory responses.
3. Total salt deposition, whether from a single exposure or a series of exposures over a longer period of time, is a reasonable estimate of hazard to plants.

In addition, dose-response data from one species should not be applied to other species for which no experimental toxicity data exists, unless some information is available on the degree of susceptibility of that species to salt loading. This restriction is intended to reduce the overgeneralization common to impact studies and to emphasize the need for more acute toxicity data on relevant vegetation. If these conditions are satisfied, then rough guidelines for permissible drift deposition can be established by comparing the maximum salt deposition (short-term highs or long-term averages) from an operating cooling tower with tolerance limits of selected species. For example, deposition ranges of 1000 to 4200 kg/km^2 per month may be representative of higher-than-average salt loading. Thus, a conservative (worst case) estimate of deposition rates causing acute foliar symptoms lies within this range. But only those species very sensitive to salt would be affected by these ambient levels.

Extrapolation of laboratory data to natural situations of operating cooling towers should be undertaken with caution until existing saltwater cooling towers are well into the post-operational stage, and a sufficient data base is available.

2.3.3 Acid Formation Enhancement by Cooling Tower/Stack Gas Interactions

The quantity and impact of acid precipitation deposition due to cooling tower/stack gas interaction have not been determined in the field. It was reported that at the Keystone Generating Station stack plumes merging with visible cooling tower plumes caused sulfate generation (a prerequisite to acid generation) as well as acid generation. This phenomenon (sulfate generation) was measured in the drift but not in the ground deposition from cooling towers at Keystone. At Chalk Point the merging plumes resulted in an increase of drift pH, as acid drift already existed in the stack plume. The observed differences between these sites is attributed to the fact that at Chalk Point a wet venturi scrubber supplies enough water for most of the acid production to occur within the stack plume before any merging with the cooling tower plume occurs. Since all new coal-fired steam-electric plants will require scrubbing, it is possible that acid production during plume merging may be inhibited because of the low SO_2 levels of the flue gases leaving the stacks.

It is possible to minimize the probability of stack/cooling tower plume merging with a knowledge of the climatology and the tower and stack designs. The climatology at a specific site will determine what stack/cooling tower orientation will limit the duration of plume merging during an annual cycle. The longest visible cooling tower plumes are produced under high relative humidities, light winds, stable temperatures, stable lapse rates, and low ambient temperatures. Evaporation of the cooling tower plume is thereby curtailed, and more water vapor from the plume is condensed. If the stack/cooling tower axis is oriented perpendicular to the wind under these ambient conditions, the stack and visible cooling tower plume will merge at distances further downwind, or perhaps not at all. With plume merging further downwind, dispersion of the stack plume can reduce the concentration level of sulfate, so that acid production at this juncture could be reduced. After determining the climatological wind rose at the site for these coincident, critical ambient conditions, the stack/cooling tower axis can be oriented perpendicular to the most frequent wind direction in which these conditions occur, thereby minimizing the plume merging and acid production. In addition, the stack and cooling tower can be designed so that under the requisite ambient conditions the final plume rise for both the stack and cooling tower will not be coincident.

Although these design guidelines should minimize merging along a vertical plane, the effectiveness of such a procedure has not been determined. The procedures to reduce cooling tower/stack plume interactions are suggestions based on the Gaussian diffusion of the plumes and Briggs' plume rise formulation, but field validation has not been established.

Acid deposition from precipitation scavenging of stack and cooling tower plumes has not been measured. At Chalk Point, the simultaneous scavenging of cooling tower and stack plumes appeared to raise the pH of rainwater over that of tower pre-operational data. However, no other studies have been conducted to measure the acid deposition resulting from simultaneous precipitation scavenging of the stack and cooling tower plumes.

SECTION 3

COOLING TOWER PLUMES

This section is intended to provide a brief description of cooling towers, the associated plumes, and the meteorological parameters which affect plume behavior. In depth discussions of the meteorological effects of vapor plumes and the ecological effects of salt drift are presented in Sections 4 and 5, respectively.

3.1 TYPES OF COOLING TOWERS

Conventional cooling towers may be classified as either wet (evaporative) or dry (non-evaporative). In the evaporative or wet cooling process, direct mixing of hot water and air results in a rapid cooling effect. This is due primarily to heat transfer by evaporation (latent heat transfer) and partially to heat transfer directly from the water to the air (sensible heat transfer). In the non-evaporative or dry process, the exchange of heat occurs between the air and the hot surface of the tubes containing heated water. As a consequence, the water experiences cooling by conduction and convection only.

Two types of wet cooling towers are presently employed in the United States for condenser cooling water: natural draft (hyperbolic) and mechanical draft wet cooling towers. Either fresh or saline (sea water or brackish water) water may be employed in this type of cooling system.

Natural draft cooling towers (NDCT) are designed to utilize the "chimney effect" produced inside the tower shell. The density differences between the ambient air entering and the moist air leaving the tower and the effective tower height provide the driving force for the natural draft. Warm water enters the tower, and cooled water is collected in the tower basin.

With mechanical draft cooling towers (MDCT), fans are utilized to move the air through the tower. MDCTs are further classified as induced or forced draft towers, depending on whether the air is pulled or pushed through the tower. They are further characterized as counterflow or crossflow, depending on the relative movement of the air and water. In crossflow towers, the air travels horizontally across the falling water. In counterflow towers, air travels vertically through the falling water. Detailed descriptions of cooling tower configurations can be found in a study by Hu and Englesson (1).

Power plants located in coastal areas use waters that contain various concentrations of salt, e.g. brackish inland waters, estuarine water or sea water.

While this permits the conservation of fresh water for other uses, the increase in water salinity reduces the rate of heat transfer.

3.2 PLUME BEHAVIOR

The behavior of cooling tower plumes and their characteristics are useful in assessing both the atmospheric effects of cooling towers and the interaction of the cooling tower plumes with stack gases. The contents of the plume, the shape and dimensions of the plume, the evaporation rates of circulating water, the amount of moisture in the plume, wind speed and atmospheric stability, plume length and persistence (visible plume length), and the effect of multiple plumes from more than one cooling tower influence the extent of interaction.

Cooling towers remove heat from condenser cooling water primarily by evaporation and reject this heat to the air in the form of a hot plume containing water vapor (2).

Depending on plant operating characteristics and local meteorology, from 1% to 3% of the circulating water flow is lost through evaporation. Evaporation is also responsible for the concentration of dissolved and suspended solids in the circulating water. Water droplets of the same chemical composition may be entrained in the plume and leave the tower as drift.

Figure 3-1 shows the contribution of the cooling tower plume to the water vapor mixing ratio of the background environment (3) within the plume. The atmosphere contains water vapor to a degree which depends on the relative humidity and the ambient temperature. In some arid or desert areas, the background water vapor content in the atmosphere is low compared to areas where natural precipitation is nominal or excessive. Consequently, the effect of cooling towers will be different in such widely different climatological zones. Where the atmosphere can supply adequate amounts of water for chemical reactions with the flue gases, the effect of the cooling tower water vapor on these reactions will be insignificant.

The shape of the plume after the plume leaves the tower is important for modeling. For towers with symmetrical exit ports (natural draft, circular mechanical draft) the shape of the plume as it exits is independent of wind direction. For rectangular mechanical draft towers, wind direction plays an important role in plume shape. A plume leaving a rectangular mechanical draft tower normal to the tower axis generally has a rectangular shape. As it moves downwind, it begins to assume a more circular shape, due to atmospheric mixing. A plume leaving the tower parallel to the tower's long axis will assume a circular shape sooner than a plume leaving the tower normal to the axis. Consequently, buoyant plumes are categorized as vertical and bent over. Vertical plumes occur in a motionless and stable atmosphere ("calm" condition); the bent over plumes (nearly horizontal) occur under "windy" conditions.

Early studies considered the rise of dry, buoyant plumes in a calm environment and used the Taylor entrainment assumption (4). Later investigations extended the treatment to moist, buoyant plumes in a calm atmosphere (5).

Other studies have provided extensive analyses of dry, bent over plumes, including transitions through various turbulence regimes. Recently, these studies have been expanded to include moist, bent over plumes (6).

Visible plume lengths (short, medium and persistent) depend to a great extent on the ability of the atmosphere to absorb moisture. In general, plumes are short in the summer, and become larger as winter advances (7).

The stabilized height of plume rise depends on the height of the capping inversion. Temperature, wind speed, and relative humidity in the vicinity of the cooling towers are effective predictors of plume rise and persistence (8).

Recirculation of and interference between the plumes from clusters of mechanical draft cooling towers have been observed. Increasing stack height and stack spacing have been shown to reduce recirculation (9).

A summary of cooling tower plume rise is given by Briggs (5). Many observations of cooling tower plume rise at the 2900-MWe John E. Amos Power Plant, West Virginia were used in comparing the calculated plume rise (using Briggs' equation and a cloud growth model proposed by Hanna) with the observed plume rise. The observed average plume rise of 750 m was higher than the computed value of 670 m from cloud growth model. Hanna concluded that his plume and cloud growth model can be satisfactorily used to estimate the plume characteristics and the development of clouds due to cooling tower emissions (10).

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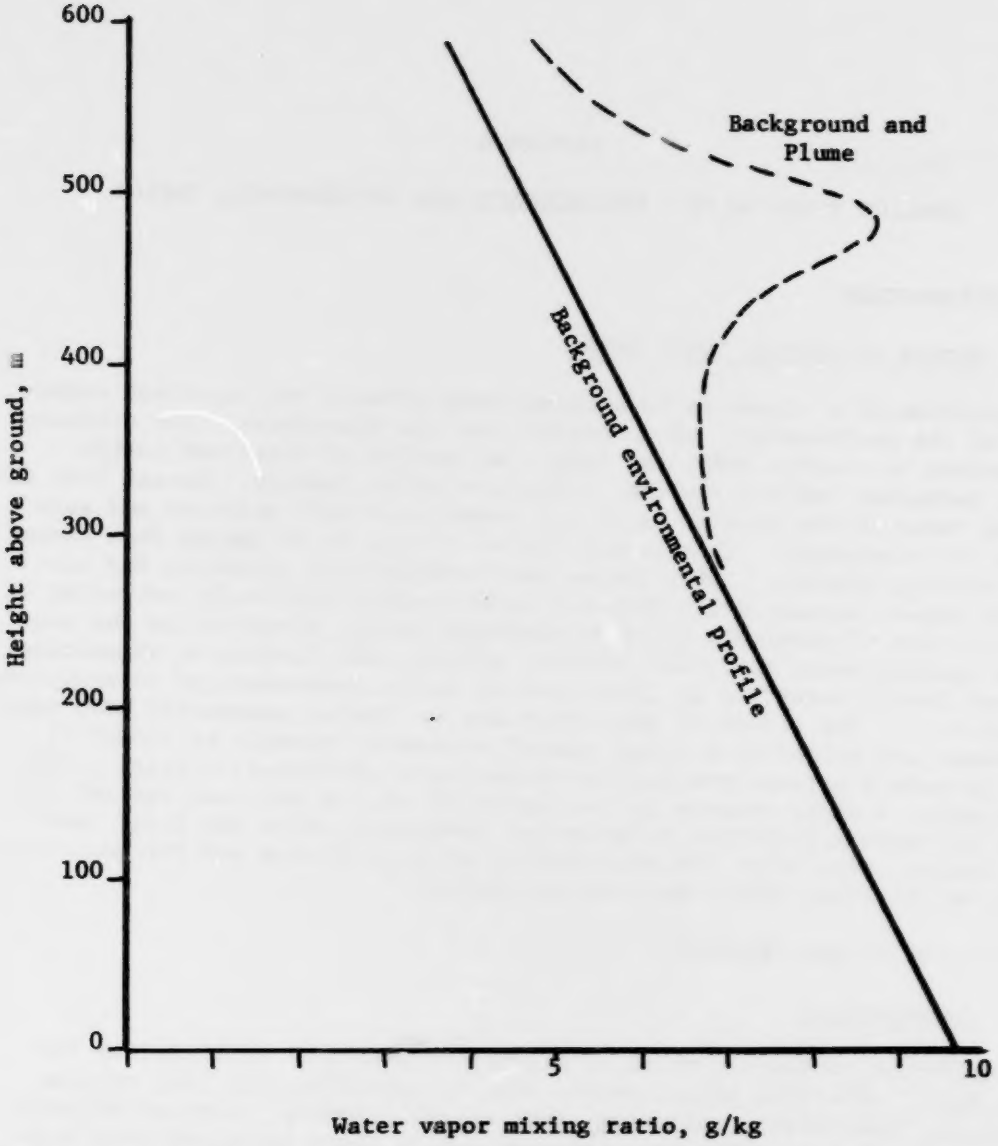

Figure 3-1 Typical vertical profile of environmental water vapor mixing ratio, with the contribution of the cooling tower plume superimposed (3).

SECTION 4

COOLING TOWER DRIFT - MEASUREMENTS AND ENVIRONMENTAL IMPACT

4.1 INTRODUCTION

4.1.1 Nature of Cooling Tower Drift

The operation of a closed cycle cooling tower affects two important components of the environment: water quality and the atmosphere. The discharge of blowdown to a water body, the result of control of dissolved solids, scale, corrosion and bio-fouling, influences water quality. Losses from the cooling tower in the form of drift and evaporation emit moisture and warm air to the atmosphere. This report considers only drift losses from closed cycle cooling systems. Drift losses have considerable potential for biological impact because drift droplets contain salts (naturally occurring or from addition of chemicals to treat condenser water) dissolved in the condenser cooling water which may increase ambient salt loading on vegetation, soil and fauna, resulting in alteration of biotic components of an ecosystem (Figure 4-1). The effect of salt drift may be further compounded when cooling towers are established along coastal waterways (oceanic or brackish) which possess a naturally-occurring higher level of dissolved salts (3000-35000 ppm). A major concern is the impact of salt on adjacent agricultural areas, or forests, with real or potential commercial value and their associated faunas. Generally, the adaptability of an ecosystem and the magnitude of the drift effect will determine the impact.

4.2 SALT DRIFT MEASUREMENTS

4.2.1 Introduction

Many different techniques exist to measure droplet size distribution and drift rate: sensitive paper, coated slides, impaction sampling, cyclone separator, laser light scattering, high volume sampling, chemical balance, and the calorimeter technique. Descriptions of their operation have been summarized in a Westinghouse study (1). For the purpose of this report, it should be noted that some instruments measure droplet size better than others, and other instruments measure mass rates more accurately (Table 4-1). Some of the instruments are mutually exclusive. The droplet size distribution from natural draft cooling towers was measured by six groups (Figure 4-2), and the droplet size distribution from mechanical draft cooling towers was measured by five groups (Figure 4-3).

Under similar atmospheric conditions, the same eliminators in the saltwater and freshwater towers will yield the same drift rate (1). Differences occur for different types of eliminators (Table 4-2); freshwater tower eliminators are usually designed to be less efficient in order to minimize pressure drop and energy penalties. Deviation between maximum and minimum values amount to a factor of 25 for natural draft cooling towers and 10 for mechanical draft cooling towers. The most efficient eliminators are sinusoidal-shaped, and limit drift values to 0.0008% of the circulating water rate.

Where there are large bodies of saltwater, natural processes (other than just cooling towers) also produce salt deposition. Surf and breaking waves form bubbles from which saltwater droplets are ejected into the air. Also, salt water vaporizing at the sea-air interface will disburse salt particles into the air. Along shore areas and during high wind conditions, the turbulent surf also adds salt droplets to the air. These facts need to be considered when reviewing salt air concentration and deposition measurements.

4.2.2 Meteorological Conditions Which Affect Deposition

Natural drift is transported over land where it is deposited either before or after water in the droplets is evaporated. Many environmental factors affect spatial deposition: salt flux, size distribution, wind speed and direction, relative humidity (RH), precipitation, atmospheric stability, topography and vegetation (Tables 4-3 and 4-4). If a saltwater cooling system is employed, other factors, such as salt concentration in the circulating water, tower exit parameters and eliminator design (Table 4-5) necessitate consideration in the evaluation of drift deposition.

Environmental factors which influence drift rate include: wind speed and direction, ambient temperature and relative humidity. Relative humidity is related to drift droplet evaporation rate. At low RH, droplets evaporate quickly to a smaller salt particle, and the fall velocity decreases. As a result, the particles remain airborne longer and impact the ground at a further distance.

Wind speed influences dispersion in two ways:

1. At high wind speeds, the vapor plume (and drift droplets) can be drawn down into the turbulent wake behind the tower structure. This phenomenon is known as aerodynamic downwash and significantly reduces the effective "release height" of the droplets. Turbulence in the wake brings the droplets to the ground quickly and results in high deposition rates close to the tower.
2. The downwind distance where a droplet impacts the ground is affected by wind speed. Droplets can be carried further during their fall by high wind speeds than by light winds. Deposition rate decreases as the square of the distance.

Tower location has a great effect on the atmospheric dispersion of drift. When a tower is located near the sea or on a bay, for example, the sea breeze becomes a significant climatic factor, whereby winds, which may predominate from one or two directions, enhance the average salt deposition in certain sectors.

Precipitation influences deposition in several ways. For example, rain tends to wash salt from the air. However, the instruments used to measure deposition are also washed by heavy rains so that deposition rates cannot be determined at these times (2). Deposition rates increase during drizzle and light rain (periods when measurements can be taken) (1). Since the rain acts as a collector, there is an inverse relationship between the salt concentration and rainfall.

In comparing cooling tower and natural salt drift, characteristics of the natural drift must be considered. The natural air concentration of salt is a function of wind direction (Figure 4-4) and distance inland (Figures 4-5 to 4-9). As the wind speed increases, a greater number of large particles are carried through the air. The average concentration tends to be a quasi-constant level between 10 km and 20 km (Figure 4-8). Increases in wind speed and precipitation rate also tend to increase natural deposition. Also, eddy motions on the lee side of obstacles increase deposition. Values ranging from 380 to 3500 kg/km^2 per month have been reported (1).

The natural salt deposition also decreases with distance inland (Figures 4-9 and 4-10). The chlorine content of rainwater decreases by a factor of 5 to 10 for inland sites (Figure 4-11 and 4-12). Quasi-constant levels begin several kilometers inland because of the more uniform vertical mixing inland, so that the removal rate approaches a more uniform value (1). Schrecker et al.(3) determined that at Forked River the concentration of salt in ambient air and deposition reach an asymptotic level of 1 ug/m^3 and 68 kg/km^2 per month, respectively. Concentration and deposition drop quickly within a few kilometers from the coast (Figure 4-13 and Table 4-6). Since the measured deposition is considerably larger than expected for the settling speed of ambient salt particles, the removal of airborne salt near the ground level is not sufficiently described by gravitational settling.

4.2.3 Saltwater Cooling Tower Drift and Deposition Measurements

Although data on salt drift from operating cooling towers is scarce, there are a few cases in which reliable measurements have been taken.

4.2.3.1 B. L. England Station, Unit 3--

Atlantic City Electric's B. L. England Station is located near Marmora, New Jersey on Great Egg Harbor Bay. Bay water is high in TSS with an average of 50 ppm, while the TDS concentration is an average 30,000 ppm. The baseload station has two coal-fired boilers (Units 1 & 2) and one oil-fired boiler (Unit 3) with a total plant nameplate generating capcity of 475.6 MW. Great Egg Harbor Bay water is used at the maximum rate of 200,000 GPM for condenser cooling. Units 1 and 2 are cooled on a once-through basis, while Unit 3 is cooled by a Research-Cottrell Natural Draft hyperbolic, counterflow saltwater cooling tower.

This is the first natural draft saltwater cooling tower of its kind in the United States. It is a small tower in comparison to existing hyperbolic towers, some of which are more than double its size. According to its manufacturer, the tower was essentially an experiment to define the state-of-the-art of saltwater cooling.

The salinity of the make up water ranges from ten (10) to twenty (20) parts per thousand with an average of sixteen (16) parts per thousand. This is concentrated by a factor of 1.5 to 2.0 in the recirculated water.

The tower emission drift parameters for the natural draft counterflow saltwater cooling tower at the B. L. England Station was field measured by Research-Cottrell Inc. (4). The station is located on Beesley's Point about 4.5 km from the Atlantic Ocean. Fifteen measurements were used to estimate the overall tower drift emission performance. The mean for the drift rate was 0.000424% of the circulating water flow with a standard deviation of 0.000123% (99% confidence level of 0.000507%). Given this background information, a discussion of salt drift-deposition at the B. L. England Station follows.

Two studies were performed: one measured drift-deposition during the pre-operational year and the other measured drift-deposition during one post-operational year. The instrumentation and measurement techniques utilized are described in a study by K. Wilber (5). The salient points were that both salt air concentration and salt deposition were measured near ground level.

In addition, the relative humidity, dry bulb temperature, and wind speed and direction were measured at each measuring station at the beginning and at the end of the measurement period.

Unusual phenomena, such as precipitation intensity and dust which occurred during the measuring period, were noted. The measuring period for salt air concentration was on the order of several hours, whereas the measuring period for deposition was about one day. This last point becomes important because over the time span of one day, the meteorological conditions vary considerably. There were only a limited number of deposition measurements in which the wind direction came from the same quadrant at beginning and end for all measuring stations (about 20) during tower operation. Therefore, the average deposition during tower operation is much more meaningful than that for any individual case. For any single wind direction sector, the average deposition value was based only upon a few cases in most instances and only in one sector do the measurements exceed 10 at any one station (Tables 4-7, 4-8). It should be noted that these wind sectors were determined by averaging beginning and ending wind directions rather than averaging interim wind directions. The salt air concentration measurements lend themselves to more reliable correlation with meteorological conditions since the measurement time period is much shorter.

Certain results can be ascertained from the raw data and the averaged data presented in the pertinent reports (2,5). For the pre-operational period, it was not unusual to observe for individual measurements anomalies in either salt air concentration or deposition. In Run No. 29, for example, the salt deposition rate was almost 500 kg/km^2-mo above background rates at Station No. 3, while at Station 4 it was about 3 ug/m^3 above background. A few miles inland, such as at Station 3, the deposition values reached a few hundred kg/km^2-mo while at the ocean front, a few thousand kg/km^2-mo was not an unusual reading. The same pattern held for salt concentration. Inland, concentration dropped from tens to a few ug/m^3. At the ocean front, readings between 50 and 90 ug/m^3 were common while values over 100 ug/m^3 occurred on occasion. These tendencies were reflected in the averaged values shown in Figure 4-14.

Wilber (5) noted other characteristics of the pre-operational data. The ambient sea salt concentration and deposition values measured at this site were generally consistent with those measured at Forked River, N.J. (3). The onshore wind components (ENE to SSW) at Beesley's Point were characterized by considerably higher sea salt concentration and deposition values than those from other directions. Both the average concentration and deposition levels decreased sharply from coast inland regardless of meteorological conditions.

During post-operational measurements, higher salt levels were observed up to about 5 km inland. During pre-operational stages, ambient levels decrease at distances of 2 km from the drift source (Figure 4-15). The change in average salt air concentrations was not as gradual as that for deposition. A marginally significant increase occurred between 0.5 and 4 km, but the shape of the averaged curve did not differ as in the case of deposition. A statement regarding the source of drift droplets at B. L. England Station is relevant. Observations of the tower during high wind conditions revealed that the major source of the drift appeared to be "blow-through" as opposed to drift exiting from the top of the tower. Blow-through occurred when strong winds swept through the tower basin and carried out large droplets of the circulating water. Measurements near the tower (within 1000 ft.) indicated that the high wind periods coincided with high salt concentrations. In early 1975, this problem occurred frequently, and high salt concentrations were recorded at Station 9 which was located adjacent to the switchyard. As a result, the 1975 data reflect the blow-through problem, which was solved later by installing larger wind screens in the tower basin.

Instances of significant individual contributions from the cooling tower were apparent. For example, in Run No. 117 an increase of about 27 ug/m^3 occurred at Station 9 with a wind speed of about 21 mph. This was the highest observed increase and a second maximum occurred during Run No. 123 under similar conditions. In the later case, the increase was about 8 ug/m^3. The changes from background values were considerable since the background was about 1 ug/m^3 in these cited cases. Since instances involving about 500 kg/km^2-mo were observed during the pre-operational phase, those occasions during the post-operational phase will be excluded in these comments. However, increases of 1000 to 4200 kg/km^2-mo over background were measured at inland stations as far as Station No. 3 (3 km inland). At Station 4 (5 km inland), measurements of more than 1000 kg/km^2-mo were observed. The total deposition, i.e. the background plus cooling tower increment, was quite large on occasion - about 10,000 kg/km^2-mo. This was observed only once at an inland station (Run No. 137). Total deposition reached 4242 kg/km^2-mo at Station 3 during Run No. 152. Usually, significant deposition varied between 1000 and 2000 kg/km^2-mo at locations up to 5 km inland. As far as 24 km inland, total deposition reaching several hundred kg/km^2-mo (Run No. 102) was occasionally measured, whereas this quantity was not observed (except for one questionable case) during pre-operational runs.

Measurements show that meteorological conditions affected deposition. For example, during light rain or drizzle, high relative humidity and winds coming from the ocean, the deposition increases (Runs No. 102 and 137). Although no analysis on the correlation with meteorological conditions was mentioned (2), such a relationship does seem to exist. Future studies should examine meteorological factors which influence salt deposition, enumerating more precise cause-effect relationships.

The comparison of pre-operational and post-operational salt levels showed that the long term average air concentration and deposition levels varied with local meteorological conditions and distance from shore. The phenomenon of blow-through undoubtedly increased recorded salt concentrations at Stations 4 and 9, which were located within 1000 ft. of the tower. The correction of this problem eliminated a major source of drift, so that average salt levels in the vicinity of the tower at present should be much lower than values indicated in Figure 4-16 (post-operational salt levels).

There are several anomalies associated with the annual averages portrayed in Figures 4-14, 4-15 and 4-16.

1. During the period November 6, 1974-November 11, 1975 at the ocean shore line the average concentration and deposition was 200 to 300% higher when the unit was operating than when it was not operating.
2. Salt concentration measured inland in 1973-1974, the pre-operational year, was approximately 4 to 5 times that measured during the operational year.
3. Concentration is apparently unaffected by the tower while deposition appears to be significantly affected.

All of these anomalies make it difficult to draw meaningful conclusions concerning the contribution of cooling tower drift to the ambient salt levels.

4.2.3.2 Chalk Point, Unit No. 3--

The Potomac Electric Power Company's (PEPCO) Chalk Point station is located at the confluence of the Patuxent River and Swanson Creek in the southeastern corner of Prince Georges County, Maryland, approximately 40 miles southeast of Washington, D.C. There are four units at Chalk Point, of which three are presently on line. The three units have a nameplate generating capacity of 1,329 MW. Units 1 and 2 are coal fired, base load boilers, utilizing 7.5 x 10^8 GPD of Patuxent River water for once-through cooling. Unit 3 is an oil fired, peaking boiler, utilizing 1.9 x 10^7 GPD of the once-through discharge water for recirculating cooling of this 600-MWe unit.

Annual average salt concentration in the Patuxent River at Chalk Point is about 7000 ppm. On a monthly basis, values range from 1000 ppm to 13,000 ppm.

The Chalk Point Cooling Tower Project (CPCTP) is the most comprehensive study of cooling tower drift and the associated environmental effects to date. In addition to numerous measurements of tower operating characteristics, the environment surrounding the Chalk Point Station is being closely monitored for any adverse effects attributable to the natural draft cooling tower. In this section, the drift measurements which have been conducted will be discussed.

Argonne National Lab has identified several field measurements as valid for use in evaluating numerical salt deposition models (6,7). The deposition measurements at Chalk Point are expressed in terms of number of droplets/m^2-hr, and are given in Table 4-9.

In another study (8), the drift measured by aircraft traverses through and around the plume was obtained. The collection efficiency for the Chemical Film Sampler used for these measurements drops quickly for droplets below 20 microns. The complete droplet distribution data summary is given in the Chalk Point Cooling Tower Project Summary (8). Figure 4-17 illustrates the distribution of two traverses obtained from flight paths such as in Figure 4-18. The mean mass diameter (MMD) is also shown in Table 4-10 for one test run.

A few comments are appropriate for the Chalk Point deposition data selected for further study by Argonne National Laboratories (6,7). ESC obtained deposition measurements in June of 1976, while ambient measurements of the winds, dewpoint, and dry bulb temperature were collected by the Applied Physics Laboratory (APL) of John Hopkins University with a 92-meter instrumented tower and radiosondes. Tower emission droplet size was measured directly by ESC, but the Israel-Overcamp-Pringle (IOP) data (unpublished) were inferred. The ESC cases tended to be for slightly stable atmospheric conditions while the IOP cases occurred during slightly unstable conditions. Hence, ESC deposition rates were about 5 to 10 times higher than the IOP rates for corresponding distances. Measured droplets of 1500 to 2500 um could reflect contamination such as rain, spray on coal piles, dew from trees, emissions from the #3 stack using a scrubber, or blowout. The ESC samplers were closer to the tower (200 to 1000 m) than the IOP samplers (200 to 3000 m). Droplets less than 100 um were not necessarily recorded although they were observed; this omission could significantly affect the total droplet deposition rates recorded. The IOP data were collected from May through July of 1975. The ambient meteorological data were measured from a microwave tower located about 1 km north of the tower, including RH, wind speed and direction and temperature (6,7).

4.2.3.3 Turkey Point--

Florida Power and Light Company's (FP&L) Turkey Point Station is located about 30 miles south of Miami at the shore of Biscayne Bay. It consists of two 430-MWe oil-fueled units completed in 1967 and 1968, and two 730 MWe nuclear units which began operation in 1972 and 1973. Condenser cooling of all four units is now provided by a closed-loop saltwater cooling canal system. The salinity of the circulating water ranges typically from 30,000 to 41,000 gpm.

Data for saltwater mechanical draft cooling towers are as scarce as those for saltwater natural draft cooling towers. In each case, salt drift information for only one or two towers have been measured. The only instrumented measurement of drift emission on a mechanical draft cooling tower was at Turkey Point in Florida (9). The tower drift fraction was measured to be 0.00027% with a drift flux of 7736 ug/m^2-sec, drift mass emission rate of 3.42 gm/s, and a mass median drop diameter of 120 um (Table 4-11). Data on magnesium and sodium components to drift emission are given in Tables 4-12 and 4-13. The measurements were taken under different load and meteorological conditions. Figure 4-19 provides a summary of the available drift emission data for the one-cell Turkey Point mechanical draft cooling tower. It is significant that this tower was designed to reduce the drift emission as compared with previous towers. The newness and the improved eliminator design combined to assure the the drift emission did not exceed that for the other operating mechanical draft cooling towers (Figure 4-20).

In another study by Hunter (10) to determine the contribution to salt concentrations by drift from the mechanical draft cooling tower, the increase in the ambient salt concentration due to the tower was less than the measurement accuracy of approximately 3 to 5 ug/m^3. The APS (Airborne Particle Sampler) stations are shown in Figure 4-21. The effect of the cooling tower on ambient salt concentration was obtained by using algorithms to estimate the background salt concentration which would have occurred during each of the cooling tower tests. This calculated background concentration was subtracted from the measured concentration to determine the salt deposition attributed to the cooling tower. When the difference was averaged over the entire 398 measurements during cooling tower operation, the average increase of ambient salt concentration over the expected background concentration was 0.002 ug/m^3 with a standard deviation of 4.8 ug/m^3. This analysis is summarized in Table 4-14. This clearly indicates that there was no statistically significant increase in ambient salt concentration during tower operation.

4.2.3.4 Additional Observations on Drift--

A series of qualitative descriptions regarding deposition from saltwater cooling towers was outlined in a Westinghouse report (1). These descriptions include reports of impacts surrounding the saltwater cooling towers:

1. A three-cell mechanical draft cooling tower in Trinidad (W. R. Grace Co.), which circulates 20,000 gpm of water a little less saline than ocean water, has had a noticable impact on surroundings. Some onsite carbon steel structures have suffered a fair amount of corrosion. Also, a sugarcane field located within plant boundaries is not as healthy as others in the area. However, it is not known whether this is caused by cooling tower drift or insufficient care.
2. A power plant in Bari, Italy uses a 12-cell tower having 132,000 gpm flow, 18,000 ppm saltwater concentration, and a measured drift rate of 0.008%. With this original drift rate, some olive trees were damaged and occasional arcing of nearby power lines was observed. A modification to the eliminators reduced drift rate to 0.0001%. Since then, no damage to olive trees or problems with the power lines have occurred.

3. Two natural draft cooling towers are located at Stella North Power Station, Lemington, England. The towers are 76 m high, 56 m at the base, serve a total of 240 MW, and have a circulating water flow rate of 52,000 gpm with 1000 ppm salt concentration. No environmental problems were experienced within the station's boundaries or beyond. However, natural growth of vegetation in the region was scarce.
4. Based upon more than 200 measurements in England conducted by the Central Electricity Generating Board on natural draft cooling towers:

   a. Overall droplet diameters range from 60 to 600 microns (um).
   b. At a distance of 400 m, the average drop is 240 um with a range between 100 and 400 um.
   c. At 100 m, the average drop size is 400 um with a range from 200 to 600 um.
   d. At 1000 m, the average drop size is 100 um with a range from 60 to 200 um.
   e. The minimum detection limit of drop diameter was 25 um.

   Most results were obtained at 90 percent relative humidity at the Ratcliffe Station (1). Although these numbers very likely do not reflect downwind droplet sizes from saltwater cooling towers because of the "solute effect" which decreases the evaporation (Figure 4-22), they do provide an idea of droplet size.
5. At Fleetwood Station, England, two natural draft cooling towers which are 76 m high and 56 m at base, serve a total of 96 MW and have a flow rate of 3700 gpm and 4000 ppm saltwater concentration (Figure 4-23).

   The station at Fleetwood is built on land reclaimed from salt marshes. Pulverized fuel ash has been used to reclaim more land which is now used for agricultural purposes. This and the health of the grass, shrubs and trees used for landscaping on the station site, all indicate an absence of environmental impact. It is worth emphasizing that the area has a typical coastal atmosphere with a natural salt burden and that the average annual rainfall is some 0.84 m. The latter is seldom less than 20 mm in any one month.

   A botanical survey of the station site listed 110 species of flowering plants, all typical local species to be expected in such an area. In the vicinity of the cooling towers the soil used in reclamation contains clay mixed with rubble and stony debris. This is largely covered with grass, clover and plantains.

   The only part of the site on which vegetation appears to have been affected by the use of seawater in the towers is a comparatively small area around their ponds. This area is subjected to the blow-out of seawater by wind and is more extensive to the east of the towers, where spray is blown by the prevailing westerly winds. This area is being colonized by a few typical salt-marsh species - Glasswort (Salicornia), Sea Spurrey (Spergularia sp.) and Common Scurvy-grass (Cochlearia Officinalis).

These two saltwater towers have been operated satisfactorily since 1955 (12). The environmental consequence of salt drift deposition from the cooling tower was field investigated (13). The field data were analyzed and the conclusions of a year's survey, as reported in (14), are:

a. The analysis of salt precipitation at sites situated around the station at distances between 400 m and 3660 m has revealed no significant difference between the salt deposition rates when winds blow from the power station or from the sea.
b. Blow-out from the base of the towers occurs even at relatively low wind speeds and gives significant deposits of salt at distances of up to at least 100 m from the towers.
c. A measurement of the quantity of salt carried upwards by the rising stream of air within a cooling tower gave a result (18 kg hr^{-1} at a tower loading of 30 MW) consistent with a calculated figure based on the design performance of the eliminators.

In summary, no problems exist with respect to the performance of cooling towers using salt water or brackish water. If the towers are within 5-10 km of the coast, it can be assumed that the on-shore drift of salt in the atmosphere will be predominant over any chlorides in carry-over from towers. On-shore drift diminishes rapidly at a distance of up to 10 km, after which the atmospheric salt burden remains fairly constant. So that if sea-water is used in towers more than 10 km inland, consideration may need to be given locally to the possible effects of carry-over, since the maximum deposition rate from a natural draft tower can occur up to 3 km away. However, in many areas in Northern Europe, the rainfall is likely to be sufficient to reduce any harmful accumulation of chloride in soil or on vegetation.

6. One mechanical draft cooling tower at the Exxon Chemical Co., Linden, N.J. has 4 cells, a flow rate of 22,000 gpm and saltwater concentration of 10 to 12 thousand ppm. Corrosion from drift is noticable from 150 to 200 m downwind of the tower. Pavement replaced the natural landscape and vegetation in the immediate vicinity of the towers so no conclusions concerning effects on plant life can be drawn.
7. Two mechanical draft cooling towers located at Chevron Oil Co., Perth Amboy, N.J. have 5 cells each. Flow rate for each tower is 12,000 gpm and salinity is 10 to 15 thousand ppm. The effects of drift were observed out to 150 m so that a routine cleaning program for nearby structures was used to reduce cor-

rosion. A tree grove 300 m west of the towers looked healthy.

Even though these descriptions are not quantitative, the design and impact descriptions do provide an estimation of the overall environmental effects. However, without knowing the quantitative contribution of cooling tower drift to natural salt levels, extrapolation of environmental effects to new sites becomes tenuous. It does seem reasonable to conclude from these case studies that any problems with excessive drift can be corrected with proper eliminator design.

4.3 ENVIRONMENTAL EFFECTS OF SALT DRIFT

4.3.1 Factors Relevant to Environmental Impact Assessment

The assessment of the potential impact of cooling tower drift on the biotic components of the environment should include:

1. A comparison of natural atmospheric salt loading to the tower salt contribution to the atmosphere;
2. An objective determination that the cumulative salt load (natural plus induced levels) will/will not harm the flora/ fauna of a region;
3. A comparison of pre- and post-operational salt levels in vegetation;
4. A determination of the salt tolerances or toxicity of plants and animals found in the area influenced by the tower (14,15, 16,17).

4.3.1.1 Naturally Occurring Atmospheric Salt Loading--

Ambient salt levels are expressed as sea salt, or near-ground level sea salt concentration in ug/m^3, and as deposition, or near-ground level deposition, flux in kg/km^2-mo (lb/acre-mo). Techniques for the measurement of these factors have been extensively reviewed (1,10,14,18). Both air salt concentration and deposition decrease with increasing distance from the sea or saline water body, approaching nearly a constant minimum several kilometers inland (Table 4-6, Figure 4-7). Natural salt drift deposition varies from one locality to another due to geography and local meteorology as well as distance from shore. Values ranging from 280 kg/km^2-mo (2.6 lb/acre-mo) have been reported (1,19).

4.3.1.2 Cooling Tower Salt Loading--

Cooling tower salt contribution to the atmosphere has been reviewed (1,10,15, 18). Generally, little data is available on natural versus induced changes in ambient levels with some exceptions. The Austin-Houghton predictive model (15) indicated that the cooling tower system at the proposed Forked River Nuclear Generating Station in New Jersey (General Public Utilities Service Corp.) would add less than 10% to the naturally occurring ambient salt levels. A study by Hunter (10) analyzing the demonstration of salt water mechanical cooling devices at the Turkey Point Power Plant (Florida Power and Light) reported that the operation of the cooling tower did not increase the background salt concentration significantly at any of the sampled stations (Table 4-14). Post-operational data from the Chalk Point Study suggested that the cooling tower operations between May 1975 and April 1976 did not significantly alter the ambient levels of atmospheric salt in an area within a 9.6 km radius of the power plant (20). However, a comprehensive analysis of pre- and post-operational background salt concentrations of a major power plant's cooling towers is needed to eliminate discrepancies in ambient salt measurement techniques, location of sampling stations, and variable meteorological conditions which occurred in existing measurements.

4.3.1.3 Cumulative Salt Load on the Biota--

A series of comprehensive studies conducted at the Chalk Point Power Plant (PEPCO), Maryland is the most complete record to date on the cumulative short-term salt load on the biota (16,20,21,22,23). For example, baseline studies with post-operational data on ion load (external and internal foliar sodium and chloride), which is a measure of the concentration of Na^+ and Cl^- available to a leaf under natural field conditions, indicated that no statistically significant differences in ion load were observed for four species of trees common to the Chalk Point Region. Damage to vegetation will be discussed in a later section.

Scientists at the Boyce Thompson Institute are studying similar problems at the proposed Indian Point, N.Y., Station (24). However, the units which use cooling towers are only in the pre-operational stages so that no meaningful comparison on cumulative salt loading can be made at this time. Although other pre-operational studies exist (15,25,26), post-operational studies should be conducted in order to determine cumulative salt loading on the biota over time.

4.3.1.4 Salt Tolerances of the Biota--

The general mechanism of salt uptake by plants and animals is relatively simple, yet distinctly different in plants and animals. Salt droplets are generated by natural surf action, cooling tower drift or, in rare cases, auto traffic over salted roads in winter and are carried by the wind and impinged on vegetation where they are absorbed by the foliage (leaves) (2,5). These droplets can pass through leaf stems in particle form or in solution or diffuse through the cuticle into the interior cell layers of the leaf (27). Salt solution uptake is rapid and efficient (28). Size or degree of hydration of saline particles determines their potential for damage to foliage (24). In other cases, salt ions may pass from the soil into the root tissue. Hindawi et al. (27) reviewed the subject of salt penetration into plants.

For a toxic reaction to occur in animals, the primary route of entry is by ingestion of sodium chloride, or related salts.

For both plants and animals a substantial body of literature exists on salt tolerances (24,26). This information is useful in analyzing detrimental effects of salt loading due to operation of cooling towers through salt loading on the biota when precise dose-response relationships are defined.

Some problems are evident with existing salt tolerance data as it applies to cooling tower drift:

1. "The direct effect of airborne salt cannot be separated from the effect of salt in the soil-solution when salt is present in irrigation water or the roadside environment;
2. The effects of airborne salt are confounded with the effects of certain environmental conditions, such as wind, humidity, or temperature at the seashore; or water stress and vehicular emissions at the roadside;
3. The characteristics of the aerosol, such as concentration dose-rate, particle size distribution, or chemical composition, to which plants have been exposed may not be known nor be similar to what is predicted to occur in the vicinity of a cooling tower;
4. The plants upon which the experimental information is based may be unrepresentative of those at the site of the cooling tower owing to the choice of crops, natural abundance, or natural selection for tolerance to environmental salt." (24)

In general, biological factors which determine plant susceptibility to salt may include stage of development, species, phenotype, and physiological conditions during time of exposure, salt deposition and accumulation rate and precipitation (24,27,28,29,30).

4.3.2 Salt Drift Effects on the Biota

4.3.2.1 Effects on Vegetation—

4.3.2.1.1 Environmental Factors Affecting Foliar Injury--Foliar injury is related to salt deposition by impaction and the exposure period of salt on the vegetation (1). The degree of deposition is determined by near-ground air concentration of salt drift source (cooling tower or saline body of water). The amount of fine salt that remains on vegetation is influenced by local meteorology, particularly frequency and amount of precipitation as well as relative humidity (RH). McCune *et al*. (24) found that the environmental conditions most conducive to foliar injury were 85% RH and the absence of precipitation during and after exposure to experimental saline mists. Swain (31) demonstrated that in low humidity conditions (less than 70% RH) salt absorption occurred immediately after a single spraying, suggesting that salt spray is absorbed while in solution. Sea water mist formed crystals on the leaves when allowed to dry after application. However, salt absorption was initially higher although much slower under "high-burn conditions", that is, 75-80% RH (Figures 4-24, 4-25 and 4-26).

Using glass slide collectors at the proposed Turkey Point Station, Hindawi *et al*. (27) recorded different deposition rates on the windward and leeward side of seashore plants. Leaves on the windward side of native vegetation showed impaction rates of 4 mg/m^2-hr. Thus, impaction rather than sedimentation accounts for deposition on vegetation in shoreline areas. The excessive accumulation of Na^+ and Cl^- ions in plant tissue on the side of foliage facing the surf or salt drift source resulting in stunted growth on the windward side is referred to as "molding" (32). Factors which increase the rate of impaction, such as wind speed and salt concentration, increase the severity and incidence of injury to plants (27).

Distance from the salt drift source may affect the degree of salt deposition on vegetation. A comparison of four predictive models of ground-level salt deposition from a natural draft tower indicates that maximum deposition (assuming extreme weather conditions) may occur 1-3 km downwind (1). However, if airborne salt levels exceed 100 ug/m^3 for several hours, acute foliar injury to deciduous vegetation would not be expected to occur in the area receiving the highest aerosol concentration at 1.6 km downwind of the cooling tower (33).

The severity, distribution and course of development of saline-induced injury is determined by the dose to which the plant is exposed (24). The validity of predicting adverse effects solely from data on total salt deposition on plants is questionable because of insufficient knowledge of effects of precipitation and dew formation on the overall pattern of saline aerosols and their availability to plants (24).

4.3.2.1.2 Acute vs. Chronic Expression of Symptoms--Symptoms of foliar injury can be broadly lumped into acute and chronic effects. According to Sprague (34) "acute" involves a stimulus severe enough to cause a rapid response, usually on the order of several hours to days, while "chronic" refers to a stimulus which continues for a long time. Acute toxicity is usually lethal, whereas chronic toxicity may be lethal or potentially lethal. With reference to salt drift, acute plant responses are probably due to high levels of salt concentration, while chronic symptoms occur in response to low levels over a long period of time. In general, more experimental data exists for acute salt toxicity than for chronic toxicity effects on the biota.

Typical acute toxicity symptoms include marginal foliar necrosis (burn), lesions, shoot-tip dieback, leaf curl, intervenial necrosis and "molding" (1,14,24). Under natural conditions, acute injury is associated with occasional periods of high on-shore winds over a 24-to 28-hour period (14) causing substantial increases in ambient salt levels (Figure 4-6). These "dry salt storms" have a noticeable effect on vegetation. Since local plant species are adapted to those occasional high-concentration short-term salt exposures, perhaps only these high values would be valid for comparisons with cooling tower contribution, at least in short-term environmental assessments (15). Foliar scorch and shoot-tip dieback occurred within three days of a "dry salt storm" which increased the ambient salt level 300% over a two-day period (14). Foliar damage, however, was concentrated on the surf-side of the coastal vegetation less than 375 m from the surf.

Under experimental conditions testing simulated drift injury, acute symptoms consisted of leaf curling and wrinkling and occasional marginal necrosis with a visible boundary between necrosis and living tissue without chlorosis (21). Leaf injury in dogwood trees after spraying with salt mist was expressed as the percentage of affected leaves divided among four categories of leaf necrosis: 0-25%, 25-50%, 50-75% and 75-100% (Figure 4-27). Symptoms of acute salt toxicity in white pine consisted of needle-tip dieback on the side of the plant facing the drift generator, whereas no symptoms of toxicity were observed on the opposite side (14). In the evaluation of dose-response of bush beans to salt mist, McCune et al. (24) classified response as positive if any induced lesion was visible and negative if not. In addition, percentage of foliar surface affected was viewed as a secondary estimation of foliar damage. In acute salt toxicity studies, it is important to correlate foliar damage to the degree of exposure, separating out non-saline induced injuries (25).

Determination of a cause-effect relation in acute toxicity symptoms of vegetation may be confounded by local environmental phenomena. For example, leaf scorch in hardwoods and needle burn in conifers were not distinguishable from symptoms of drought injury (35). Sodium and chloride may interfere with normal stomatal closure, causing excessive water loss which results in leaf necrosis similar to that caused by drought (36).

Chronic effects on vegetation are less obvious but may include a chlorotic condition in the interveinal regions, lighter coloration of leaves, slower growth or changes in plant community structure and diversity (1,29). There exists a relation between yield of citrus trees and measured airborne salt concentration near the Mediterranean coast. Lomas and Gat (37) demonstrated that levels of natural salt drift decrease with increasing distance from shore and that reduced citrus yield was associated with higher loading near the coast. Chloride injury to tobacco is not always observable either in foliar tissue or in decreased yield but may affect the slow rate of burn, the even-burning properties, and the qualities of the leaf (38). Plant age and degree of exposure to salt aerosol affected bush bean yield (expressed as mean plant pod dry weight) under experimental conditions (27). Whereas three- and five-week old plant pod yield did not show noticable reductions with experimental treatment of salt aerosol, one-week old plant pod yield was reduced markedly by treatment concentrations of 25 and 75 ug/m^3, respectively (Figure 4-27). In simulated drift studies, cooling tower basin water caused foliar injury at high doses, hence it was recommended that future drift studies apply lower doses to determine chronic effects on sensitive species (23).

In general, the chronic effects of long-term exposure to low levels of ambient salt drift (naturally occurring or cooling tower induced) are not known (14).

4.3.2.1.3 Plant Differences in Susceptibility--Plant species characteristically demonstrate a full range of tolerance to salt loading along a spectrum from very sensitive to tolerant (14,19,24). Tolerances of selected species are included in Tables 4-15, 4-16 and 4-17. Lettuce, stone fruits and tobacco are some of the agricultural crops which may show a decreased yield because of saline toxicity (38). Under experimental seawater spray treatments, ornamental vegetation such as flowering dogwood, golden rain tree, red maple, trumpet creeper, Virginia creeper and wild black cherry, may be adversely affected by high salt-aerosol concentration (38). Because long-term field studies of cooling tower drift on vegetation are lacking, future experimental studies on salt drift toxicity should include tests on a range of tolerant to sensitive species found naturally or formed in the environs of the cooling tower (14,24).

4.3.2.1.4 Salt Levels that Cause Injury to Vegetation--Salt damage to vegetation has been well documented in the literature and good summaries are available (1,27). Emphasis in this section will be placed on key studies which present quantitative data on ambient or experimental salt levels that cause responses in plants. The rationale for presenting this information is to formulate a data bank on salt toxicity to plants from which rough limitations on cooling tower drift rates may be extrapolated, if possible. Areas discussed below include: natural salt levels which cause injury, natural foliar salt accumulation associated with injury, roadside runoff of deicing salts which cause injury, and experimental concentrations that induce salt toxicity symptoms.

Field data from the proposed Forked River Power Plant on natural aerosol concentrations causing damage are about all that exist. Damage to deciduous plant species was a function of distance from shore during a "dry salt storm" (Table 4-18). The conclusions of this study were:

1. The lower threshold for foliar injury to deciduous species was associated with an airborne salt concentration of about 100 ug/m^3 for several hours during the growing season. Evergreen species were less sensitive than deciduous varieties.
2. Long-term average values of less than 40 ug/m^3 produced no visible leaf scorch or related injury for the plant species studied.
3. Airborne salt concentration greater than 10 ug/m^3 may have long-term effects on the distribution and growth of plants.

Future investigations of power plant sites in the pre-operational stage should attempt to determine the nature and extent of influence of natural background salt loading on local flora.

Foliar absorption and accumulation of Na^+ and Cl^- are known to be toxic at high concentrations, causing marginal necrosis in many woody plant species (17). When leaves accumulate approximately 2000 ppm Na^+ or 5000 ppm Cl^-, symptoms develop (39). The naturally occurring seasonal variation of foliar Na^+ and Cl^- for four species native to the Chalk Point, Maryland, area are presented in Table 4-19. Large accumulation of Cl^- in dogwood foliage may be a potential bio-indicator of salt drift (17). Chloride concentrations in lombardy poplar and dogwood were, respectively, 2105 ppm and 3436 ppm Cl^- and did not seem to cause symptoms of foliar injury in those species (22). However, avocado and grapefruit showed Cl^- toxicity symptoms below 5000 ppm Cl^-. Moderate leaf scorch in Vermont silver maples was observed at concentrations of 2000 ppm Cl^- (41). Table 4-20 presents a partial list of Na^+ and Cl^- levels which may cause toxicity symptoms in selected species (22).

Studies of plants along highways where deicing salts have been used provides some information on salt toxicity symptoms in vegetation. Salt drift from deicing compounds near Canadian highways was correlated with injury to evergreens during the winter season (42). Injury in red pine decreased linearly over 115-395 ft. from the roadside, while the amount of injury correlated with foliar Cl^- concentration (Figure 4-28. Higher than background levels of Na^+ and Cl^- occurred at depths to 18 inches and at distances of 75 ft. from the road (41). Using silver maple as an indicator of salt injury to vegetation in the area, moderate leaf scorch was observed in leaves containing 0.2% Cl^-, whereas burning, defoliation and tree death were associated with concentrations greater than .5% Cl^- in leaf tissue. Holmes (43), however, cited little damage to sugar maple, oak, ash, hickory, black birch and white pine resulting from winter road salting procedures. For Holmes' data, salt deposition rates of 700-4000 lb/acre-mo (78500-449000 kg/km^2-mo) over a 3.5-year period failed to effect foliar injury to sugar maples in the area; furthermore, these deposition values exceeded natural salt drift at seashore localities by a factor of 3 to 17 (1).

Garber (44) demonstrated that spraying beans and lettuce with a 5% salt solution caused foliar injury. In greenhouse experiments, the degree of foliar injury was related to exposure time of seawater mist application (Table 4-21). Scientists at the Boyce Thompson Institute reported that greenhouse plants developed marginal wilting in plant leaves when exposed to a salt aerosol concentration of 900 ug/m^3 for 30-40 minutes with salt particles ranging from 100-150 ug in diameter (45). Moser (14) observed that the exposure of bean plants to 100 ug/m^3 sea salt mist for 12 hours resulted in acute injury, whereas exposure to 10 ug/m^3 for 48 hours had no detrimental effects. Extensive leaf damage in soybeans with salt spray treatments of 7.28 and 14.56 kg/ha-week has been reported (19). Yield reduction for soybeans occurred at the 7.28 kg/ha-week treatment and for corn at 1.82-3.64 kg/ha-week treatment. In addition, younger leaves demonstrated greater sensitivity than older leaves in soybeans; while in corn, the opposite was observed - namely, older leaves were more sensitive than younger leaves to salt sprays.

Comparing Tables 4-22, 4-23 and 4-24, a noticeable reduction of the metabolic index is apparent with application of salt spray to corn and soybeans. Such a diagnostic tool would be useful in comparing pre- to post-operational effects of cooling tower drift on vegetation, provided the necessary baseline data on foliar concentration of major ions are available.

Simulated salt drift leaf injury in dogwood was induced by repeated application of salt spray with a mechanical sprayer apparatus (21). Marginal burn symptoms appeared after the two highest treatments and the percentage of affected leaves was directly related to the number of spray treatments (Figures 4-29 and 4-30). The degree of leaf injury is presented in Figure 4-27.

McCune _et_ _al_. (24) estimated that foliar necrosis and premature loss of affected foliage on the most susceptible species of plants at Indian Point, New York, was induced by total salt deposition greater than 2.4 ug Cl^-/cm^2 in 6 hr. The most susceptible species in this study were flowering dogwood, white ash, and Canadian hemlock (Tables 4-25 and 4-26).

In addition, when white flowering dogwood and white ash were exposed at 70% RH, no foliar symptoms were induced at concentrations of 800-1700 ug $Cl^- cm^{-2}$ for 6-20 hours, but at 85% RH aerosol concentration of 1500-1700 ug Cl^-/cm^2 induced foliar injury (Table 4-27). The effect of humidity may be related to the deliquescence of NaCl around 75% relative humidity, thus increasing penetration of salt deposited on leaves at the higher humidities (75-85%) (24).

Figure 4-31 depicts the dose-response relationship of bush bean to aerosol mist experimental treatments (24) for three factors: aerosol deposition, particle size and relative humidity. The amount of injury produced by dosage around the median effective dose (ED_{50}) was from 5-10% of the foliar surfaces of the affected leaves. The ED_{50} for an aerosol with 95% of particles between 50-150 um in diameter was 48 ug Cl^-/cm^2. An increase in relative humidity from 50 to 85% during the exposure period increased by two-fold the incidence of injury in bush bean plants for the same exposure.

The incidence and severity of injury to bush beans increased with increasing foliar salt concentration (27). In general, low levels of injury were observed at the 5 and 25 ug/m^3 treatments, whereas more extensive damage and higher foliar salt accumulation was apparent at the 75 ug/m^3 salt concentration (Table 4-28). These studies indicated that in order to detect detrimental growth effects, foliar salt levels must be high enough to produce "moderate" amounts of injury, approximately 5-25% of the leaf area. The associated toxicity level for five-week old plants ranged from 900-12000 ppm Na^+ and 6300-41000 ppm Cl^- for lower and upper limits of injury, respectively (Table 4-28). The degree of foliar injury appears to be correlated with aerosol concentration, at least for the tested values of 5, 25 and 75 ug/m^3 (Figures 4-32 and 4-33). The dose-response relationship for salt spray induced injury to bush beans indicated that their sensitivity to salt spray increases with age (Figure 4-34). The median effective dose (ED_{50}) for five-week old plants is approximately 70 ug/m^3, whereas the ED_{50} for the one- and three-week old plants is around 165 ug/m^3.

Foliar injury has been reported as a consequence of several cooling systems. At Turkey Point, Florida, introduced cultivated plants (bush bean) showed visible foliar damage and elevated salt concentration in their leaves, indicating the combined influences of the cooling device and east wind drift exposure only at the exposure site which is closest (215 m) to the cooling canal spray modules (27). Tobacco plants placed closer (150-200 m) to mechanical draft cooling towers accumulated more chromium and had less total leaf weight than those located 600-1400 m away (46). Feder (47) cited foliar salt injury for several woody species downwind from a saline spray canal. No significant increase in leaf Cl^- concentration for native perennial vegetation (Virginia pine, black locust, sassafras and dogwood) occurred during the partial operation of the Chalk Point cooling tower in 1975 (16). Other workers at the Chalk Point Site found similar results for soybeans, tobacco and corn (20). The paucity of studies monitoring drift effects of operational cooling towers on vegetation necessitates a concentrated research effort before real impacts can be determined. Table 4-29 lists current information on the effects of cooling tower drift on the environment.

Salt problems on vegetation related to soil salinities and irrigation with saline water were treated extensively (1,36,39,48). Salt levels available to plants are a function of:

1. Background salt concentration of ground and surface water,
2. Salinity of irrigation water,
3. Highway runoff that may contain deicing salt compounds,
4. Cooling tower and natural salt spray drift additions.

In discussing the effects of cooling tower drift on soil and its associated vegetation, it is necessary to consider the added effects of drift salts on agro-ecosystems and on natural communities, whose biotic components and sensitivities to salt have already been determined through evolutionary time. Estimates of salt deposition from a cooling tower are numerous but have little basis in reality if not measured from operating cooling towers. For example, an increase of about 18 mg Cl^-/l in the salinity of irrigation water containing 200 mg Cl^-/l is expected in arid zones, assuming all surface salt (using maximum deposition values from the cooling tower) dissolved in irrigation water. In terms of increased salinity, less than 1 mmhos/cm was added. This appears negligible when compared to the levels of non-saline and non-alkaline soils, which have less than 4 mmhos/cm (1).

Plant response to changes in soil characteristics are generally due to changes in total salt level (osmotic potential) of soil water, or to species-specific sensitivity to sodium and chloride (1). Increased levels of soil sodium affect plants directly or indirectly. Direct effects may include alteration of the nutritional balance in plants, resulting in calcium deficiency. This occurs at levels as low as 4-5% of the exchangeable sodium in sodium-sensitive crops such as almonds, avocado, citrus and stone-fruits (49). Indirect effects include inhibition of plant growth due to poor aeration and water transmission. Such changes may result if the quantity of absorbed Na^+ is greater than 10-15% of the total exchangeable soil cations (51).

Toxic levels of chloride have been documented to some extent in the literature. Specific phytotoxicity is reported for almonds, avocado, citrus, stone fruits and grapes (1). Chloride ion uptake with Ca^{++} is twice that of Na^+ and may be associated with a co-ion effect (50). Non-sensitive crops thrive well in soil solution of 850-4250 mg/l Cl^-, while tolerable loading for irrigation water is usually less than 1700 mg/l Cl^- (1). However, Bernstein et al. (36) reported injury to almonds, citrus and stone fruits for irrigation water with a concentration of 100-175 mg/l Cl^-.

Plant tolerance to various soil salinities is sometimes a function of age (1). For example, beets are salinity sensitive during germination (Figure 4-35) but are salt tolerant in later stages of growth (Figure 4-36). At Chalk Point, Maryland, the results of the first year of cooling tower operation indicated no appreciable accumulation, or change, in soil pH, Mg, P, K, Ca, or Na (20).

A series of reference graphs have been compiled and are presented in Figures 4-37 to 4-41. This data should be used in future salt drift monitoring studies which investigate soil salt loading from cooling towers and its effect on crops and other vegetation. Again, the need for comparison of pre- and post-operational data is recommended to determine real or potential effects on vegetation.

4.3.2.2 Salt Deposition Effects on Land Vertebrates, Freshwater Fish and Other Animals--

The detrimental effects of cooling tower salt drift on the fauna in the region of the cooling tower are generally considered negligible (1,26,38,51, 52). Edmonds et al. (38) mentioned that synergistic responses to inert aerosols (NaCl) and pollutants such as SO_2 have been observed but only in extremely sensitive animals exposed to high experimental concentrations of SO_2, exceeding 20 ppm. Salt tolerances of animals are reviewed by Wolgast et al. (26). For easy reference, Table 4-30 includes a listing of salt tolerance studies reported through 1972.

Few pre-operational cooling tower studies exist which have attempted to determine salt loading and its possible consequences on the fauna. Bird impaction studies at the Three-Mile Island Nuclear Plant evaluated the nature and extent of mortality or injury to birdlife in the area (29). The results of this 15-month study showed that no increase in mortality occurred during the operation of the cooling tower when compared to pre-operational data (Table 4-31). No data, however, was recorded on the effects of salt drift on the avian component of the region. Wolgast et al. (26) estimated the potential effects of salt drift on land-dwelling vertebrates from a proposed saltwater cooling tower (Forked River, New Jersey) and anticipated no direct physiological effects on vertebrates for the expected salt loading at the site. In fact, a greater abundance and diversity of small mammals were observed in the coastal maritime vegetation community, an area of high ambient salt loading (15) than in the mainland habitats (53). No information was found on drift effects on fish.

Although excess salt may cause detrimental effects, and animals do have opportunities to ingest excessively salty food or water containing enough salt to cause osmotic changes in excess of the amount regulatory mechanisms can handle, current theories suggest that, at least for mammals and insects, some animals have evolved salt receptors warning against hypersalinity (54). This evidence of parallel evolution suggests that compensatory mechanisms for excessive salt loading may exist, thus allowing some species to regulate their salt intake, regardless of ambient concentration.

In addition to the direct physiological changes reported, indirect effects to land vertebrate populations are possible if vegetation communities are altered significantly by salt drift effects (26). The magnitude and direction of these changes cannot be predicted until data is gathered on the long-term effects of cooling tower drift on the biota.

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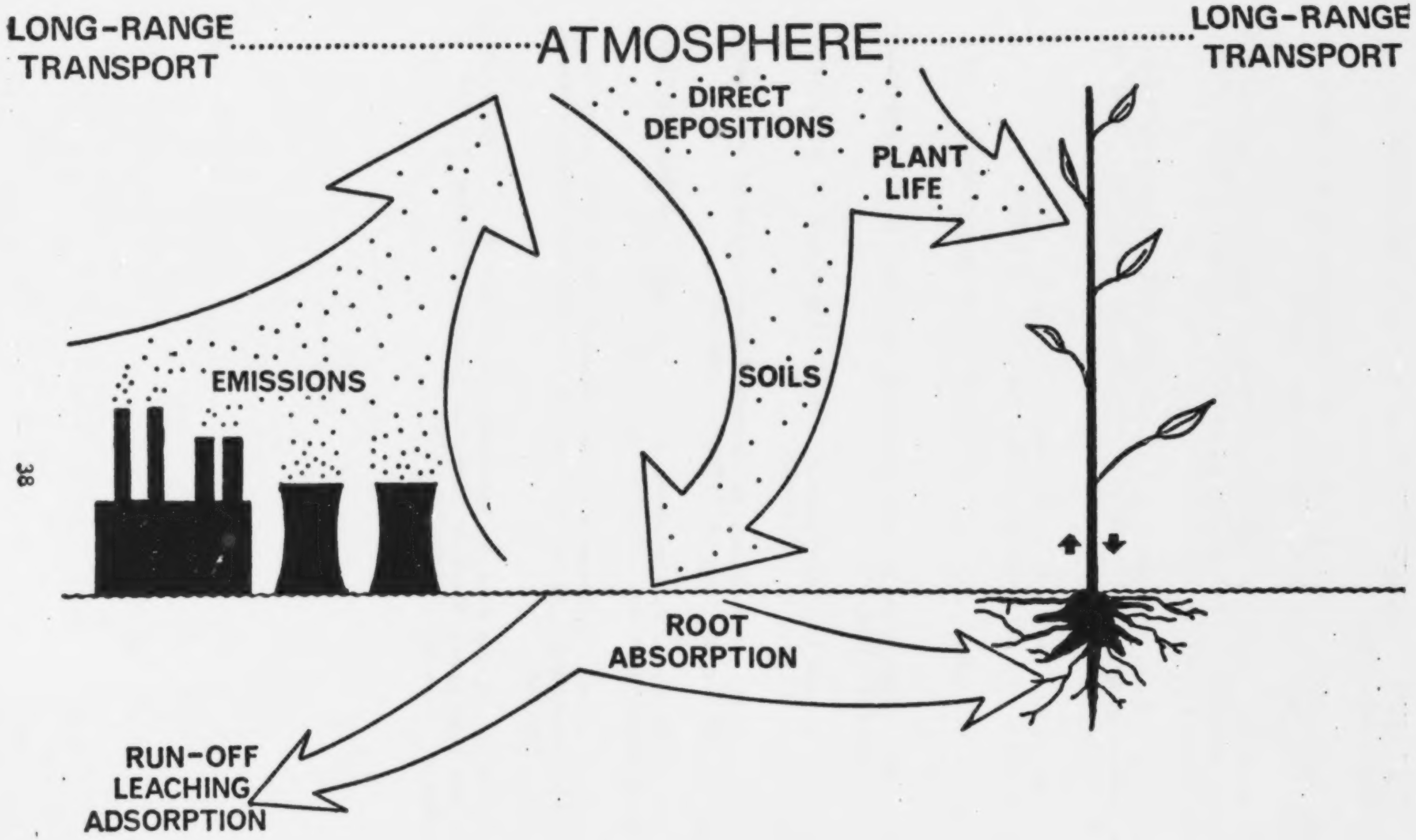
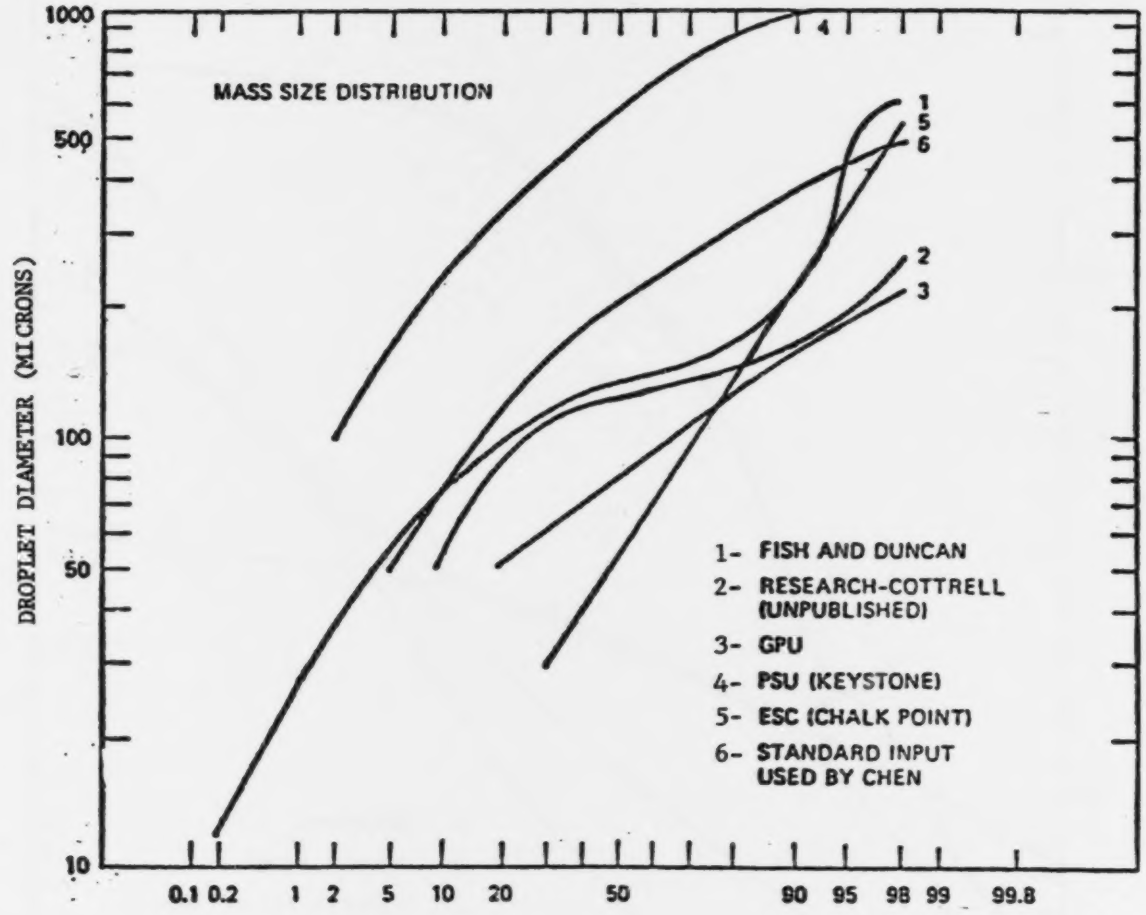


Figure 4-1 Scheme showing the possible relationships between emissions and direct depositions on soils and plant life (21)



PERCENT PROBABILITY OF TOTAL MASS SMALLER THAN STATED

Figure 4-2 Cumulative mass distributions of drift droplets for natural-draft cooling towers (59)

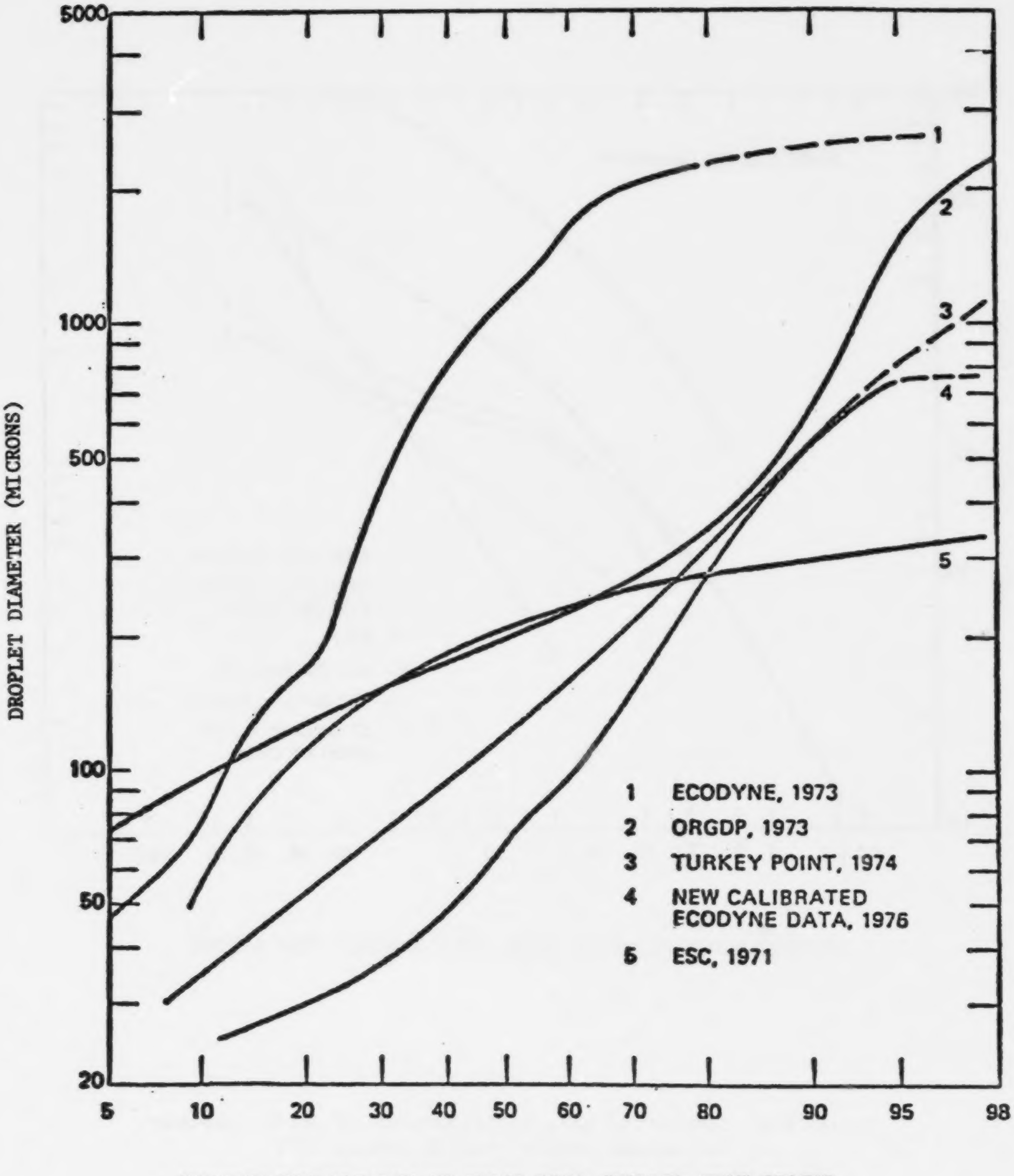


Figure 4-3 Cumulative mass distributions of drift droplets for mechanical-draft cooling towers (59)

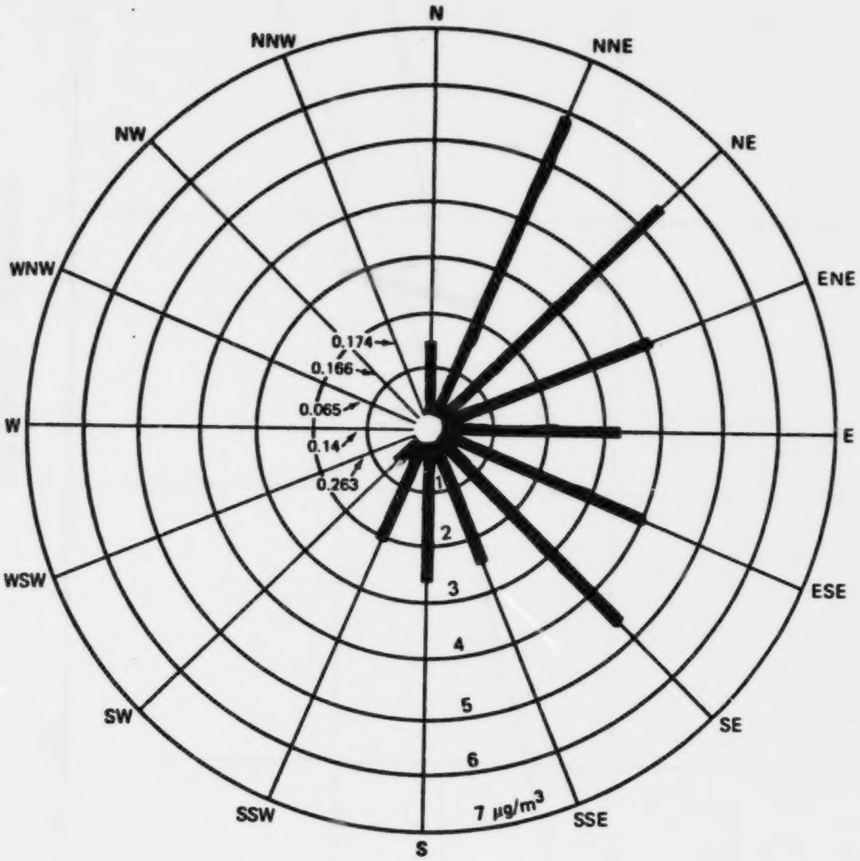

AIRBORNE PARTICULATE CONCENTRATIONS

Figure 4-4 Airborne sea salt collected at Station 4 (3)

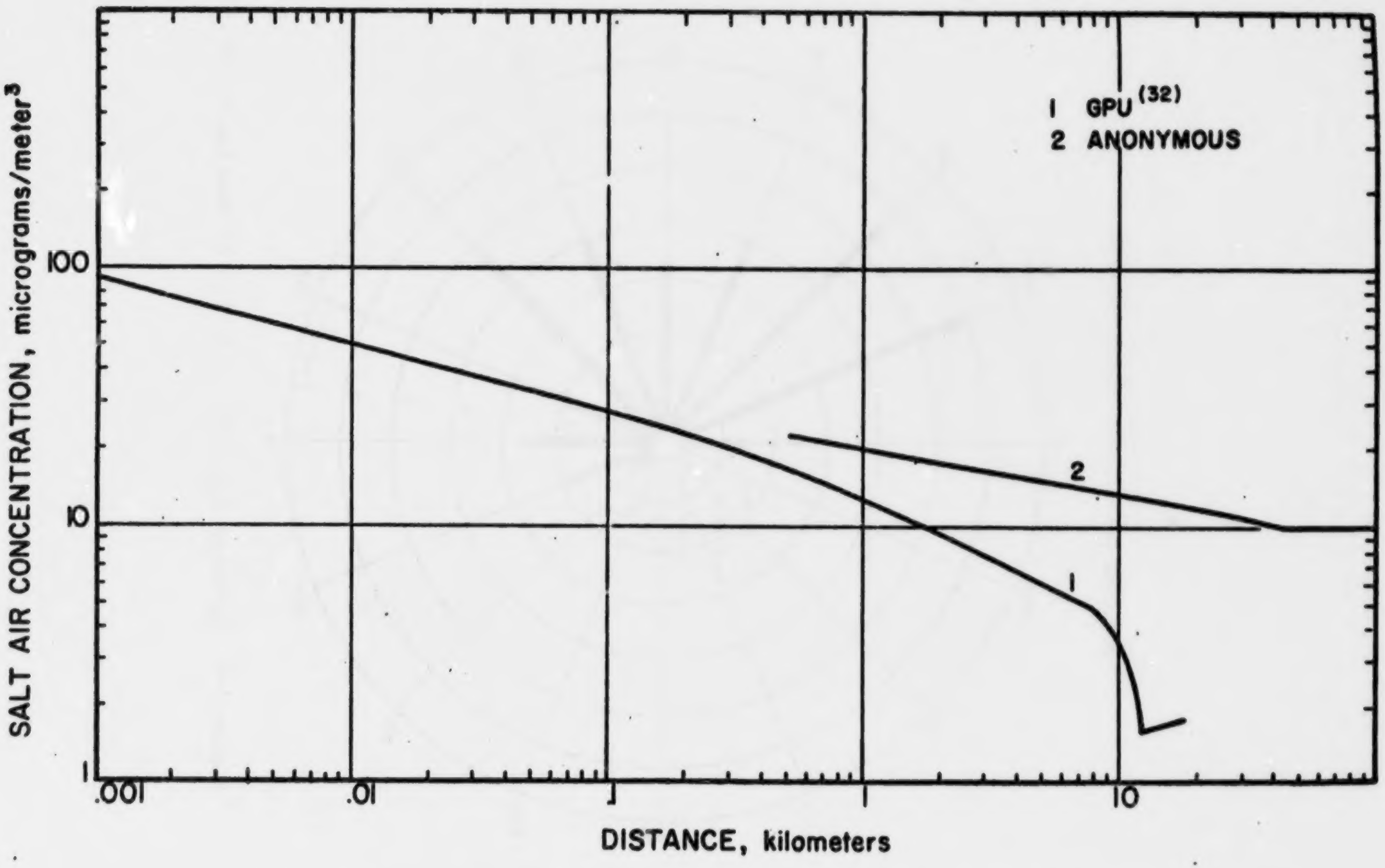
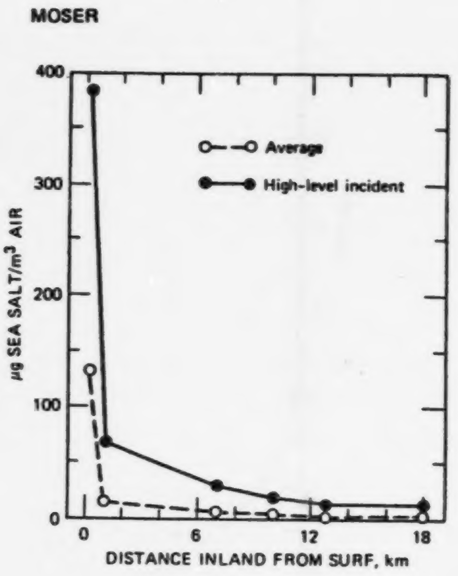


Figure 4-5 Air Concentration of Salt Drift As A Function of Distance From The Sea (1)

Fig. 4-6 Airborne salt concentration ($\mu g/m^3$) as affected by distance inland from the surf (14)



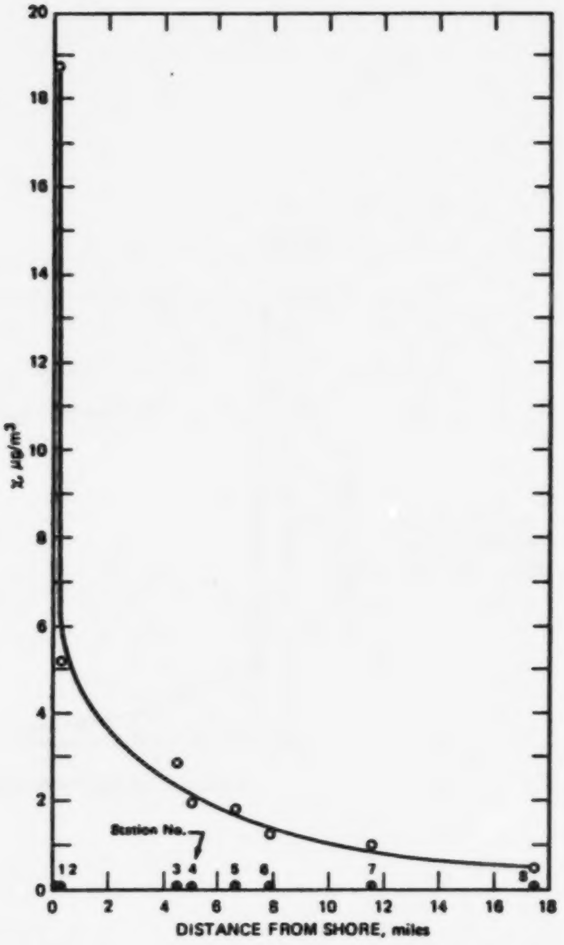


Figure 4-7 Ambient (sea salt) airborne salt concentration as a function of distance from the shore

Forked River Saltwater Cooling Program (15)

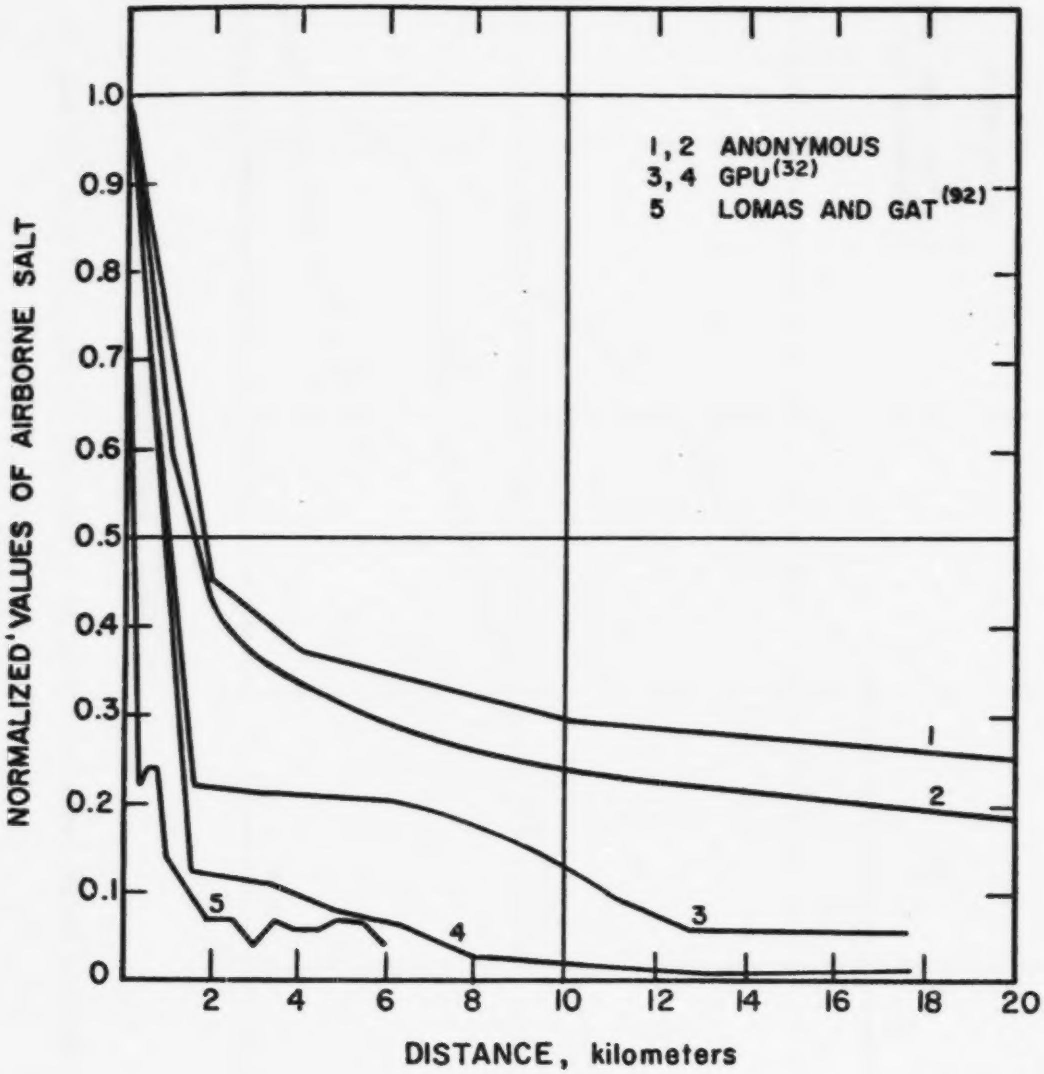


Figure 4-8 Normalized Airborne Salt Values As A Function Of The Distance Inland (with an Initial Value of One at Sea Shore)

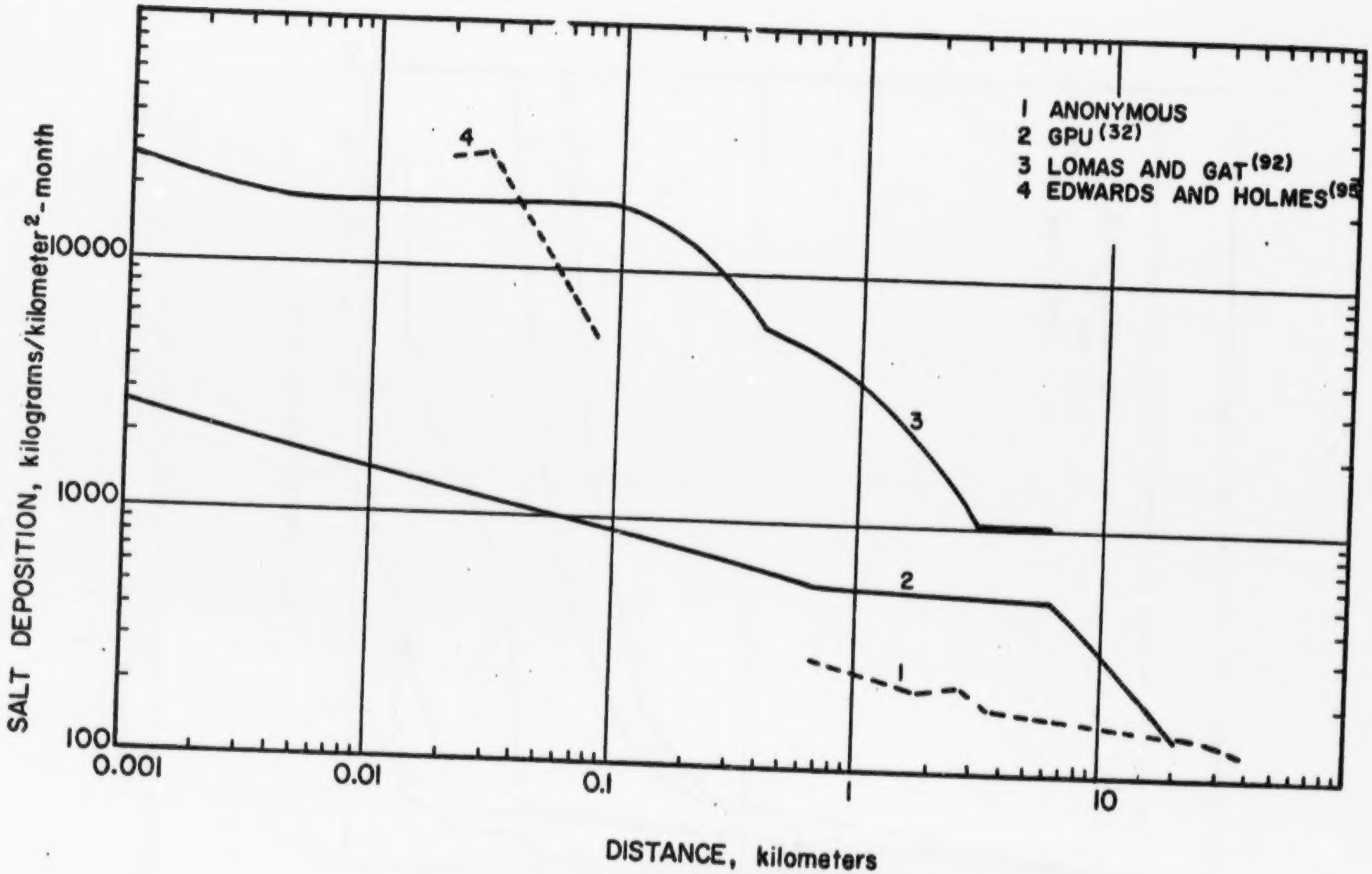


Figure 4-9 Natural Drift Deposition Rate As A Function Of Distance From The Sea (1)

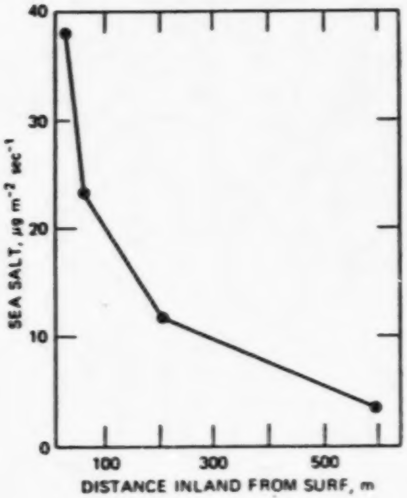


Figure 4-10 Sedimentation rates of airborne salt as affected by distance inland from the surf (14)

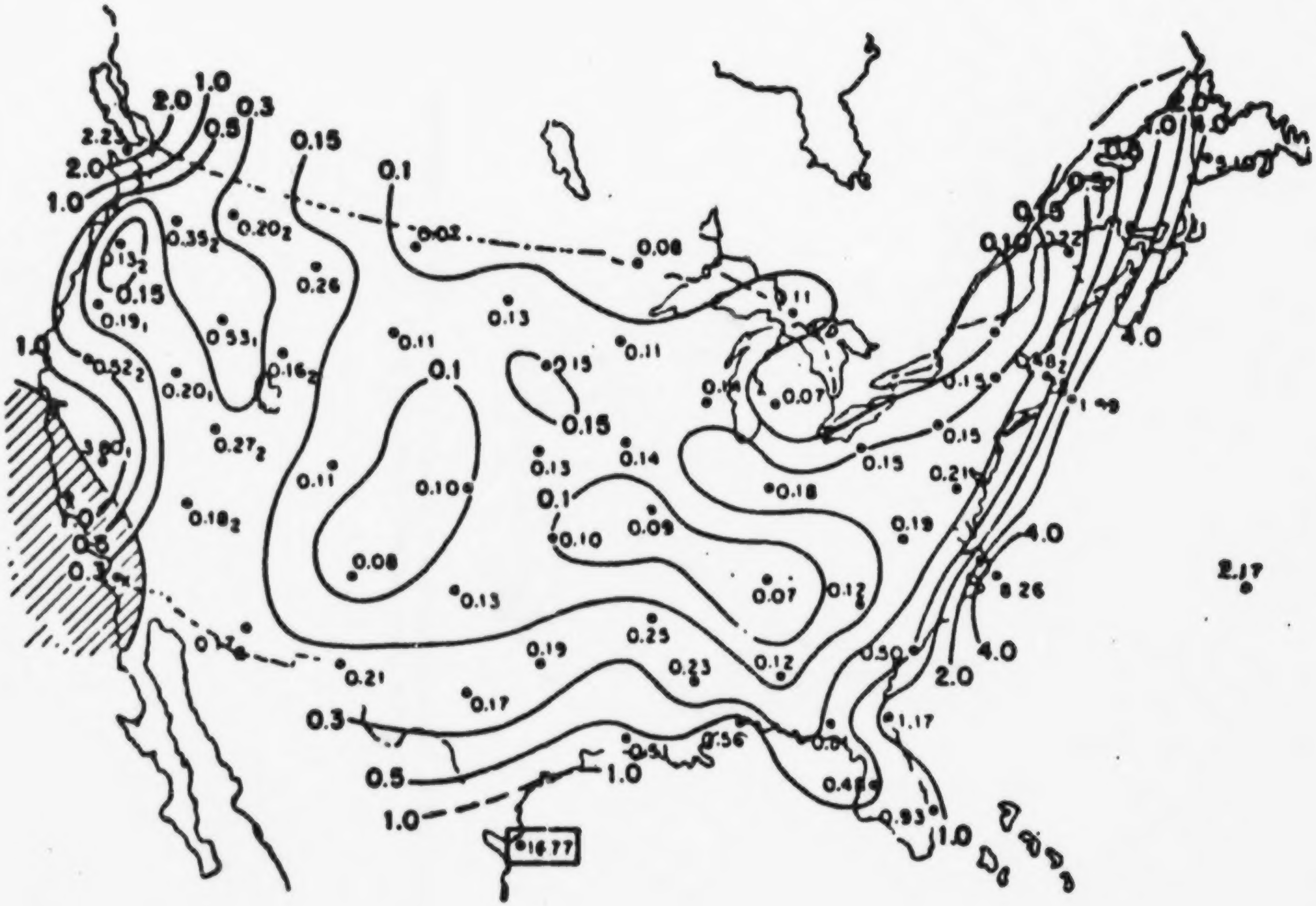


Figure 4-11 Average Cl^- Concentration, mg/l In Rainwater, July-September 1955 (61)

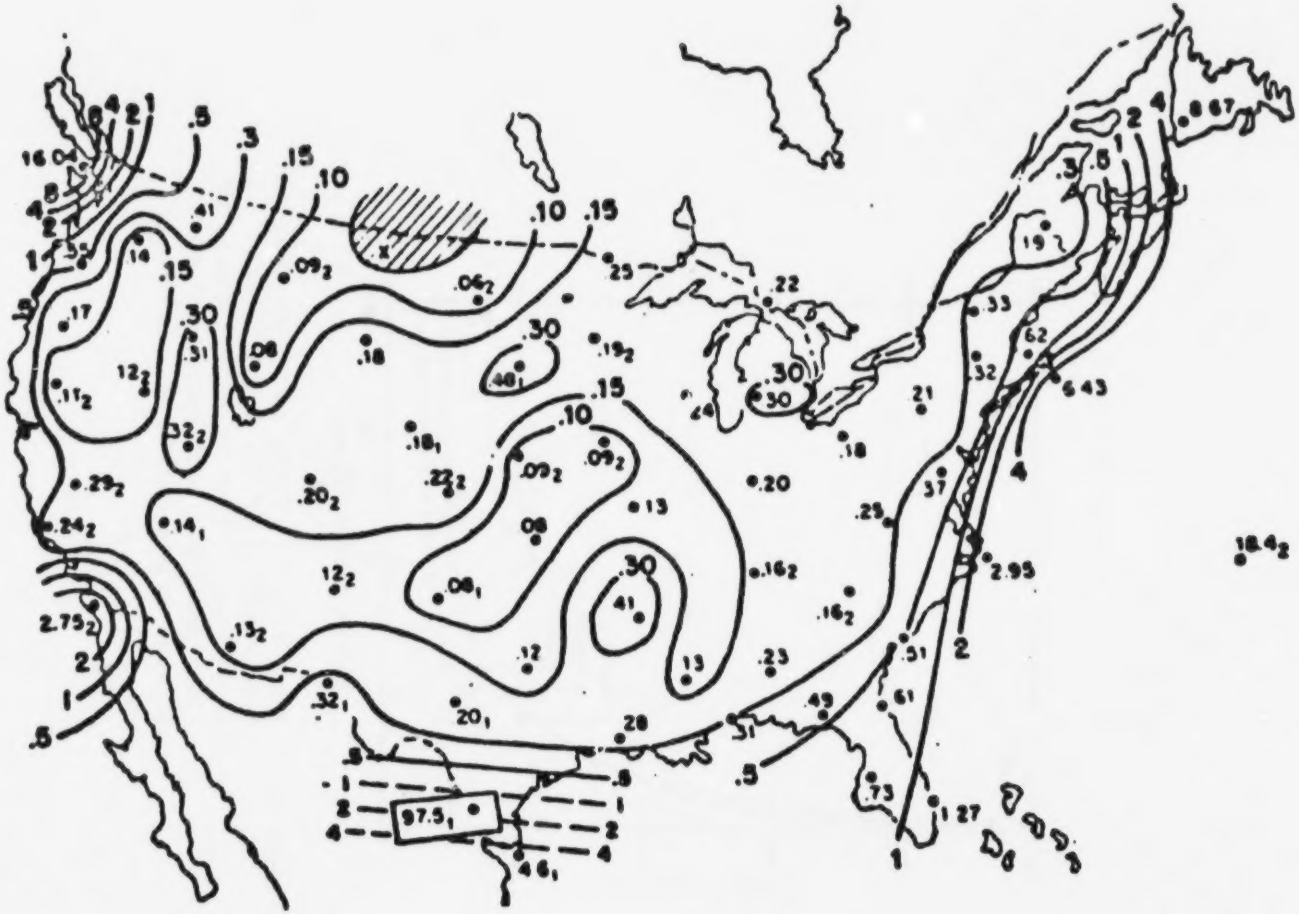


Figure 4-12 Average Cl⁻ Concentration, mg/l In Rainwater, January-March 1956 (61)

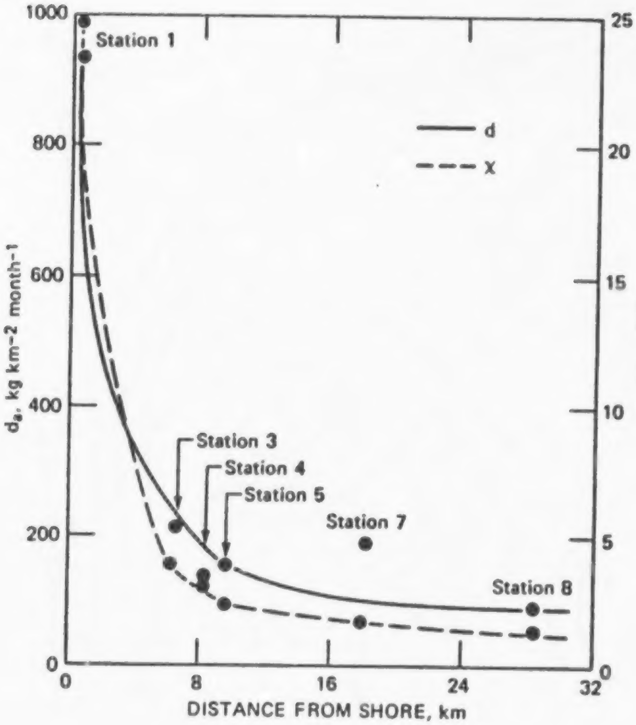


Figure 4-13 Exemplary data for χ_a and d_a in the near vicinity of the Oyster Creek Generating Station at Forked River, NJ. (Data published with permission of General Public Utilities.) (15)

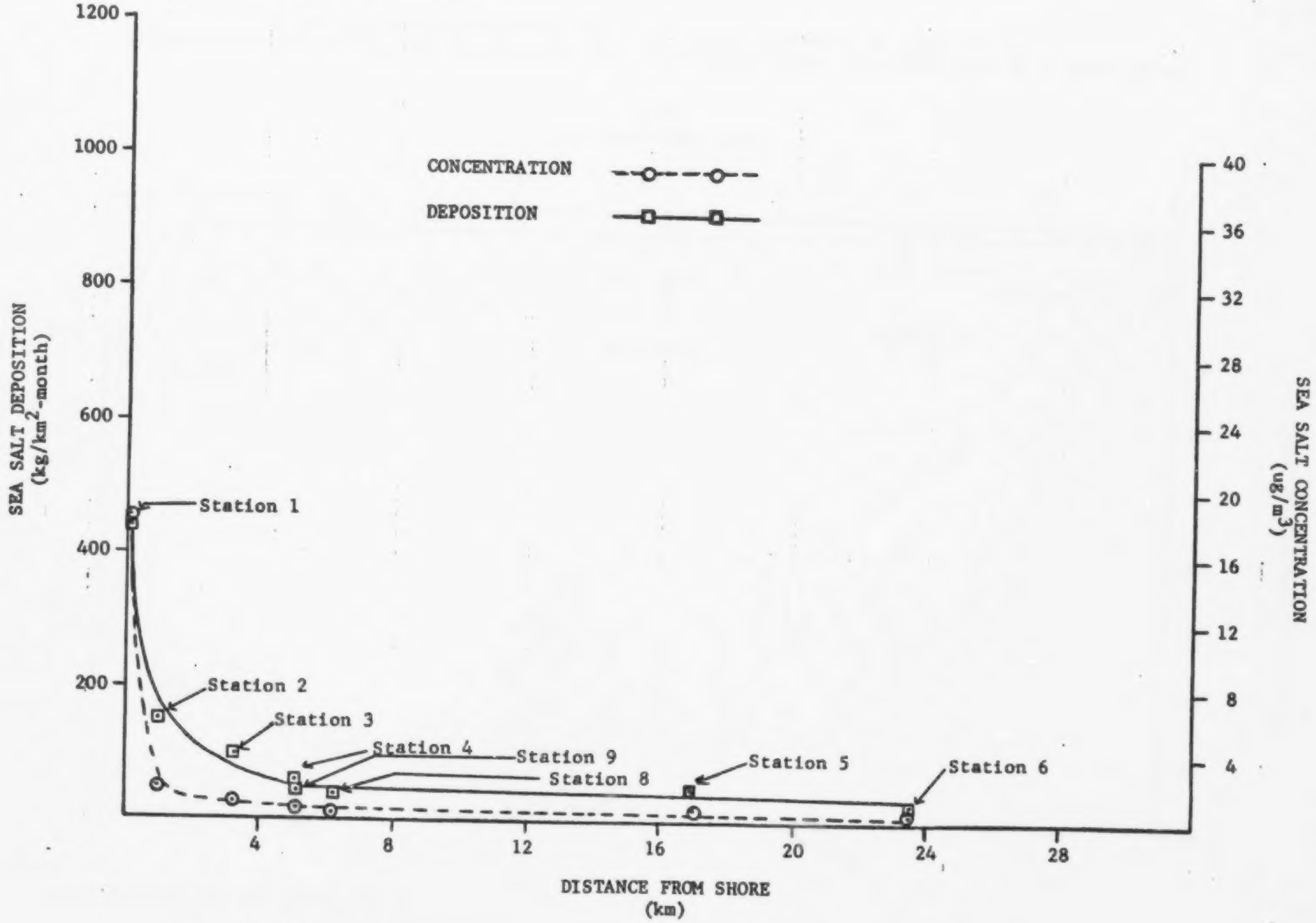


Figure 4-14 Average Sea Salt Concentration and Deposition as a Function of Distance from the Shore (November 6, 1974 - November 11, 1975) (Unit Operation: Off During Entire Test Period) (6,7)

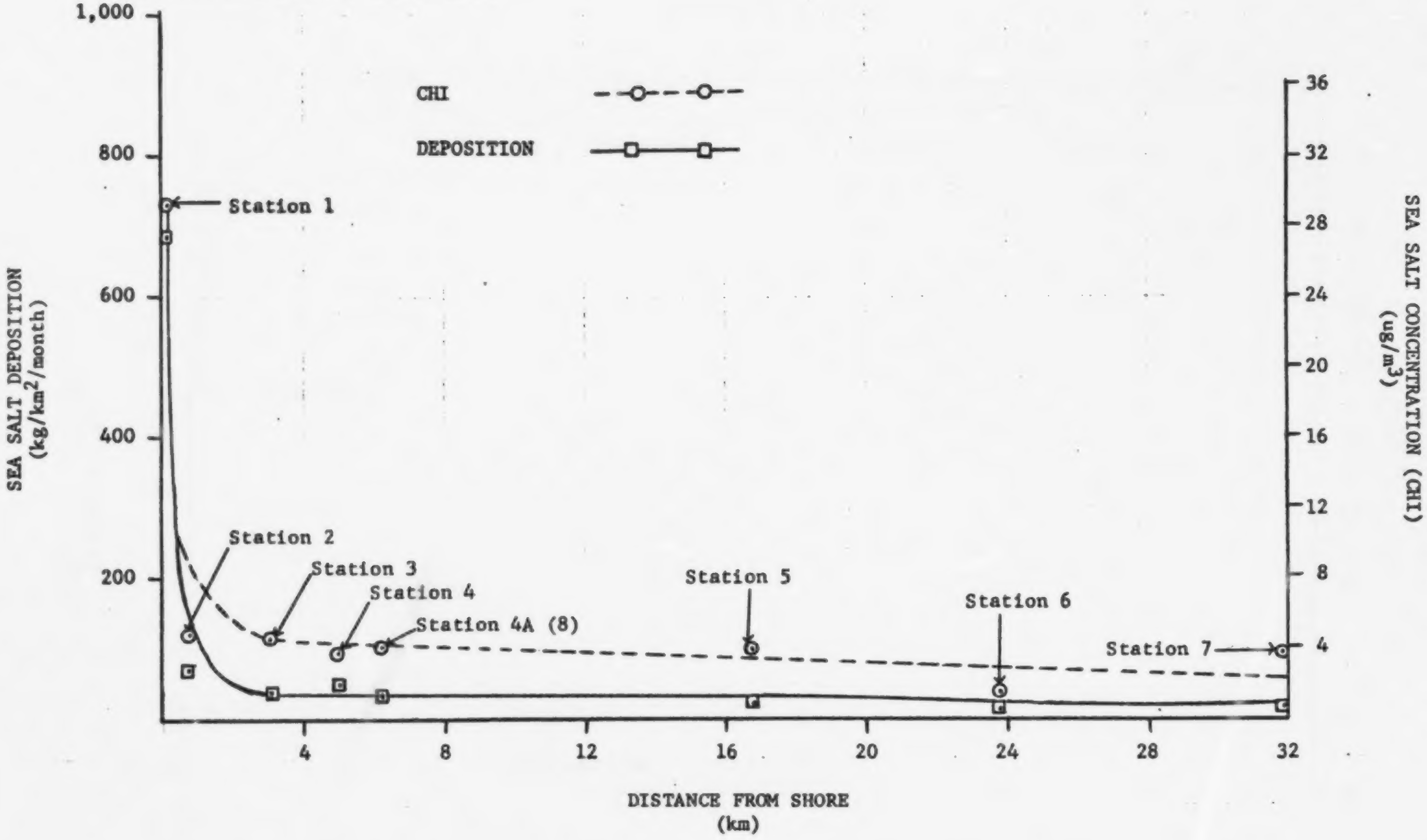


Figure 4-15 Average Ambient Ground Level Sea Salt Concentration and Deposition as a Function of Distance from the Shore (November 20, 1973 - November 5, 1974) (6,7)

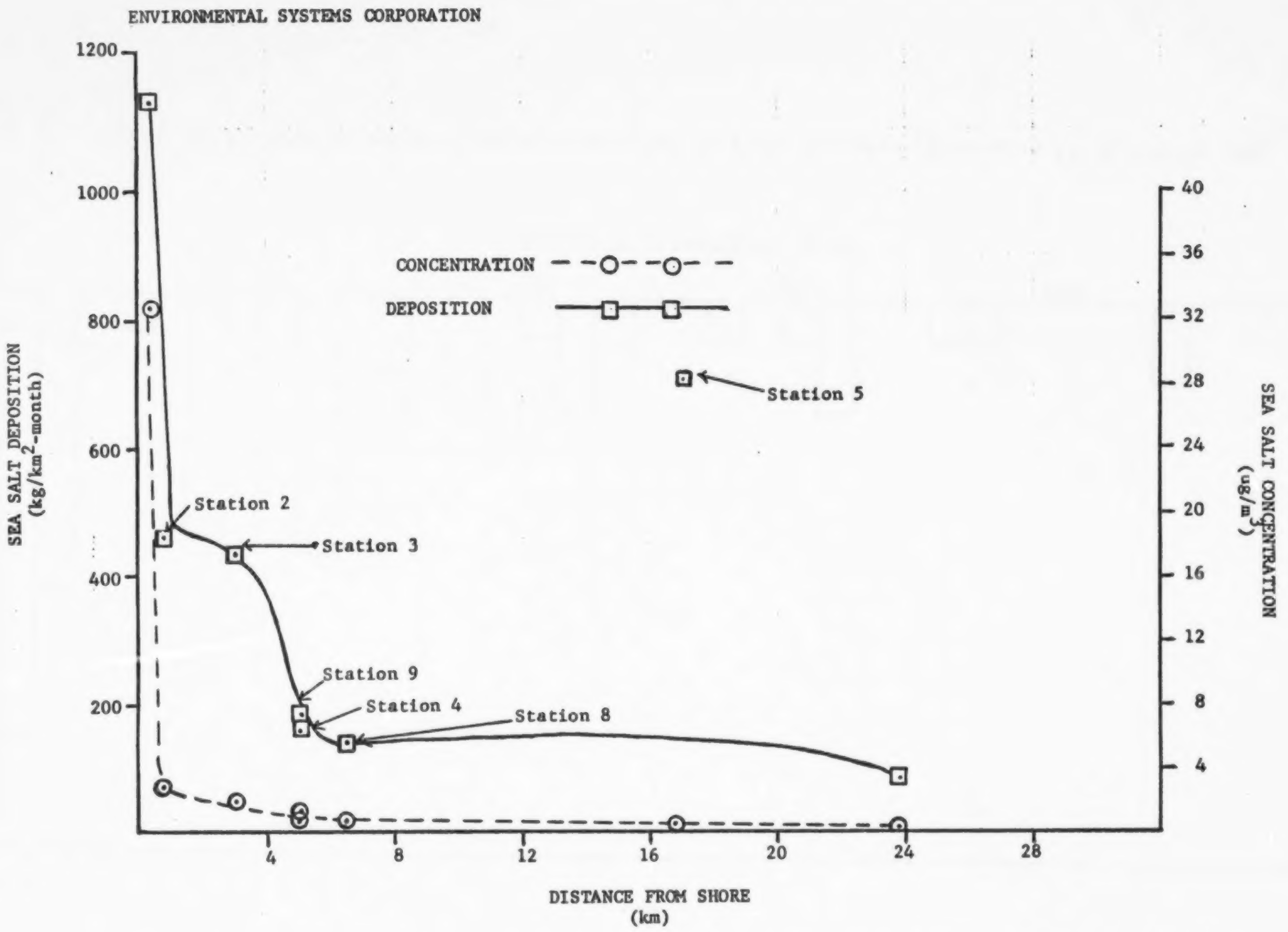


Figure 4-16 Average Sea Salt Concentration and Deposition as a Function of Distance from the Shore (November 6, 1974 - November 11, 1975) (Unit Operation: On During Entire Test Period) (6,7)

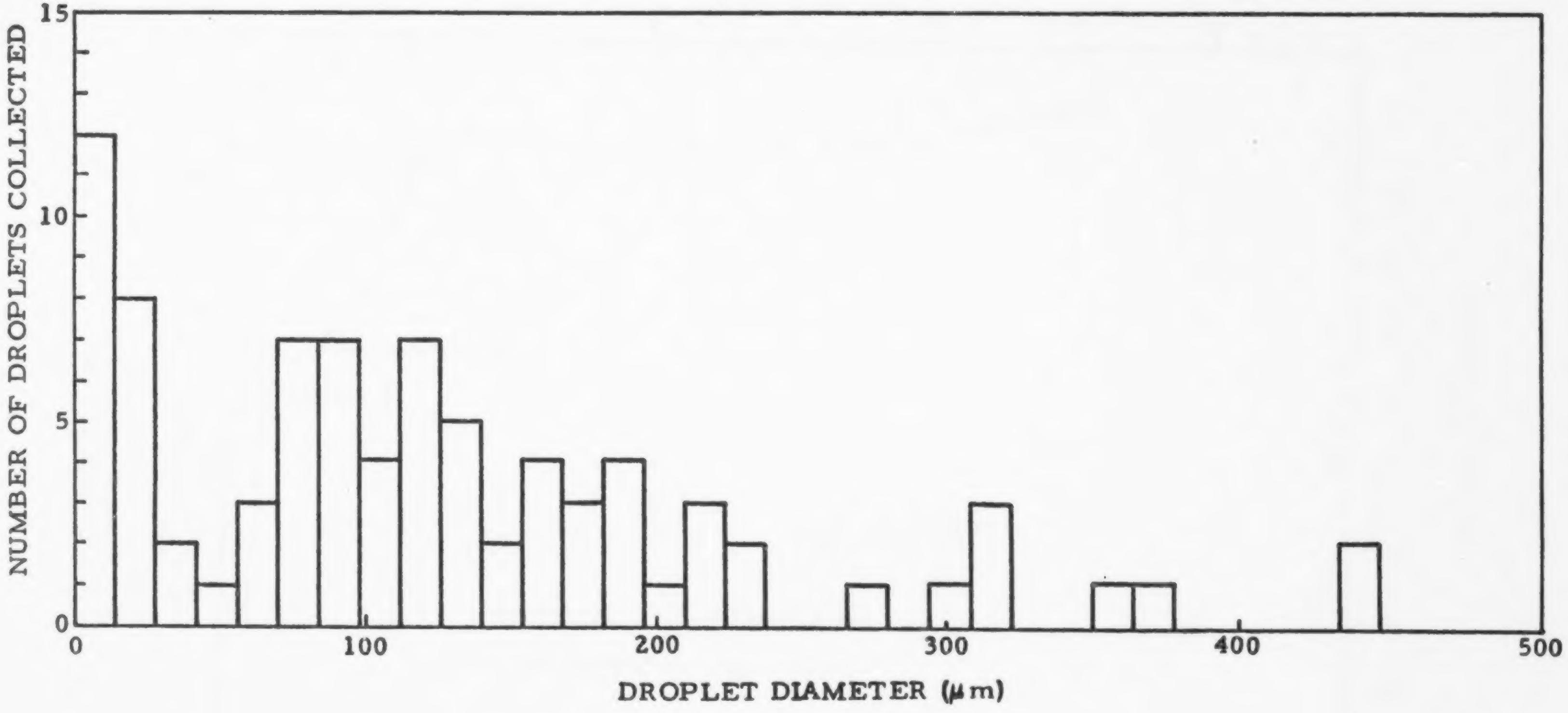
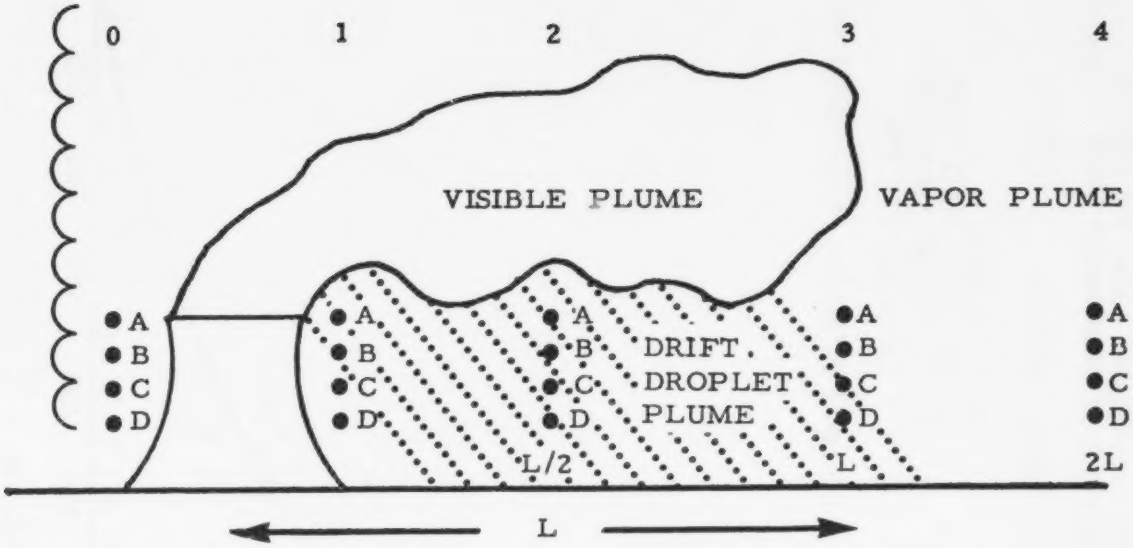


Figure 4-17 Histogram of Droplets Collected by Film Sampler (Traverse 15-8, 15-9) (8)



DOWNWIND DISTANCE:

0. Upwind from source.
1. As close to the tower as safety permitted.
2. Approximate midpoint of the visible plume (L/2).
3. Near end of the visible plume (L).
4. Approximately double the visible plume length (2L).

ALTITUDE:

A. Just below the visible plume.
B. Intermediate level between the visible plume and ground.
C. Intermediate level between the visible plume and ground.
D. As close to the ground as safety permitted.

SAMPLING MODE:

● Horizontal Traverse.
ξ Vertical Temperature Sounding.

Figure 4-18 Drift Droplet Plume, Test Plan No. 2 (8)

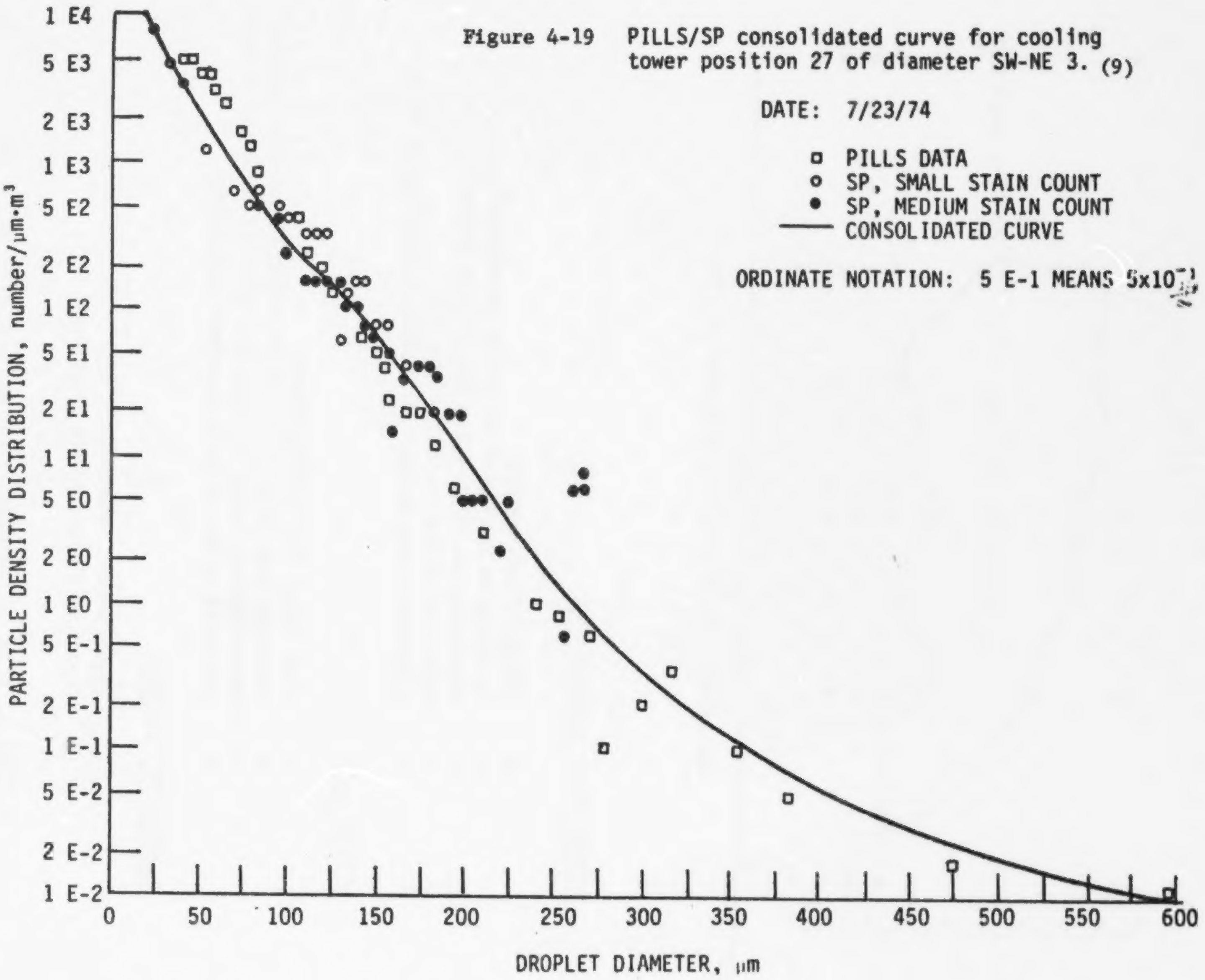


Figure 4-19 PILLS/SP consolidated curve for cooling tower position 27 of diameter SW-NE 3. (9)

DATE: 7/23/74

ORDINATE NOTATION: 5 E-1 MEANS 5×10^{-1}

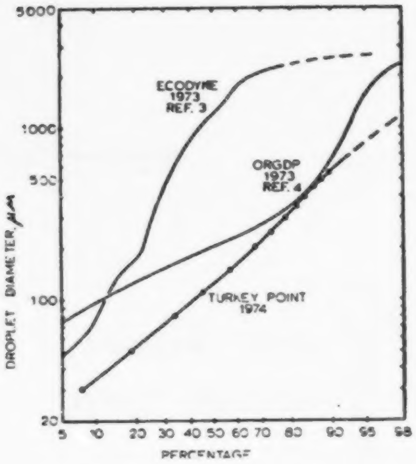


Figure 4-20 Cumulative drift distributions of three mechanical-draft cooling towers (9)

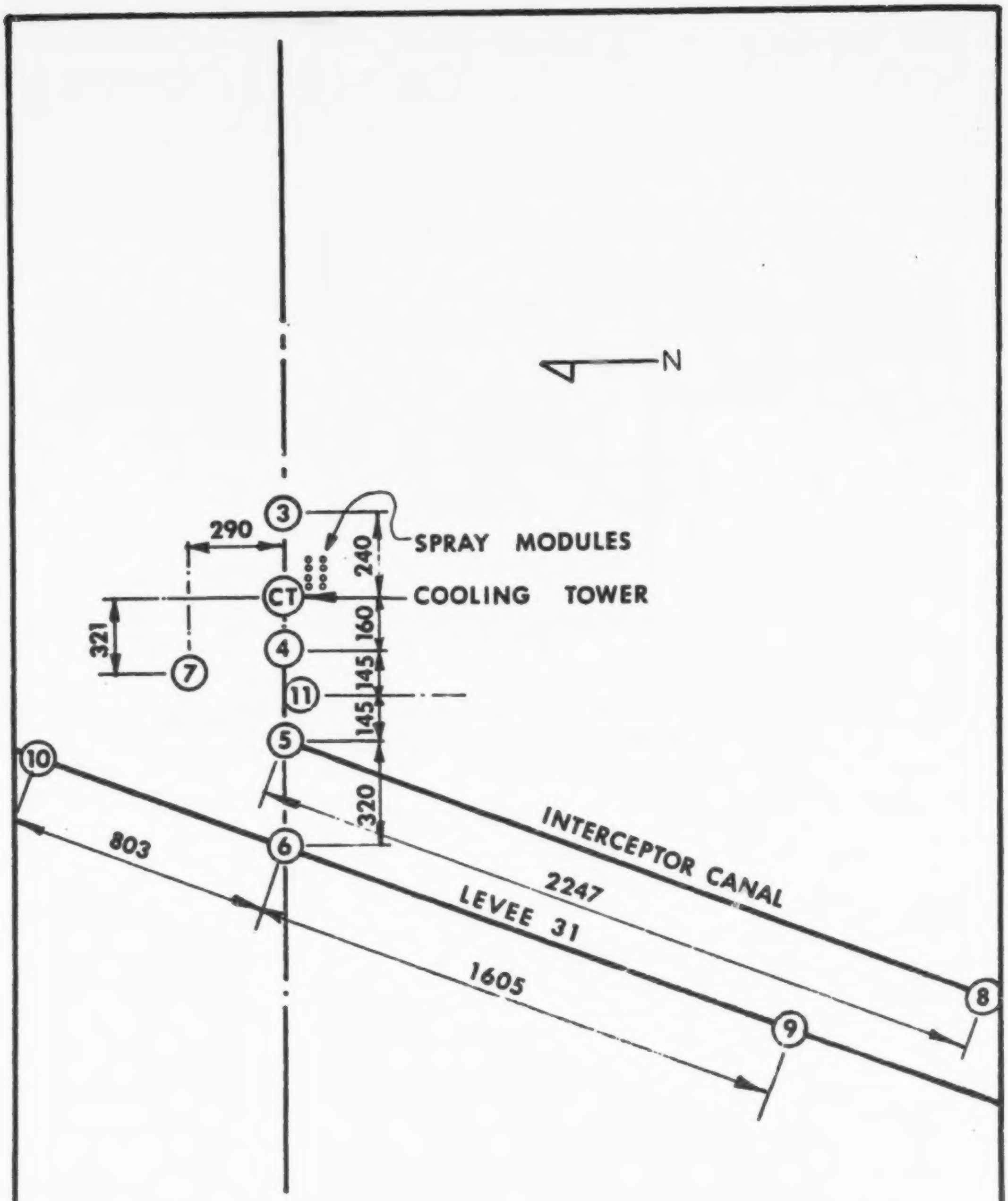


Figure 4-21 APS station locations for monitoring ambient air salt loadings and salt contributions from cooling device sources. January 1974 - July 1974. Distances in meters.(10)

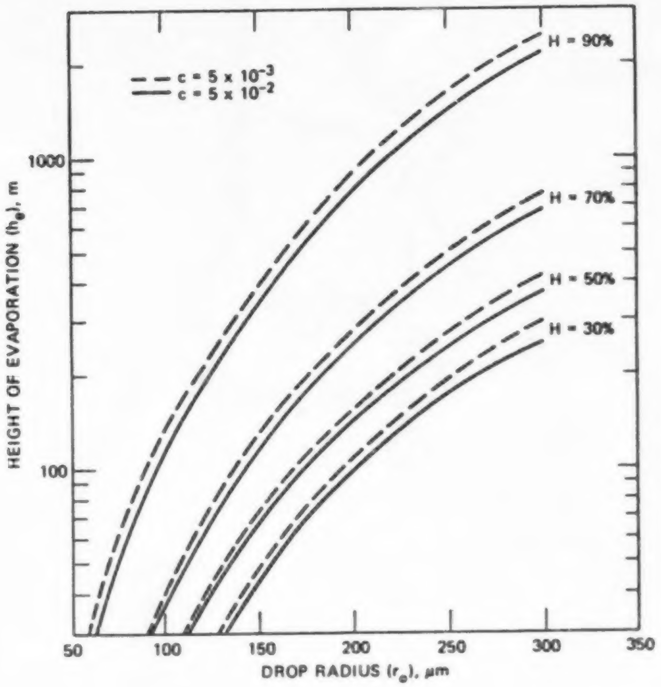


Figure 4-22 Height of evaporation of drift drops (1)

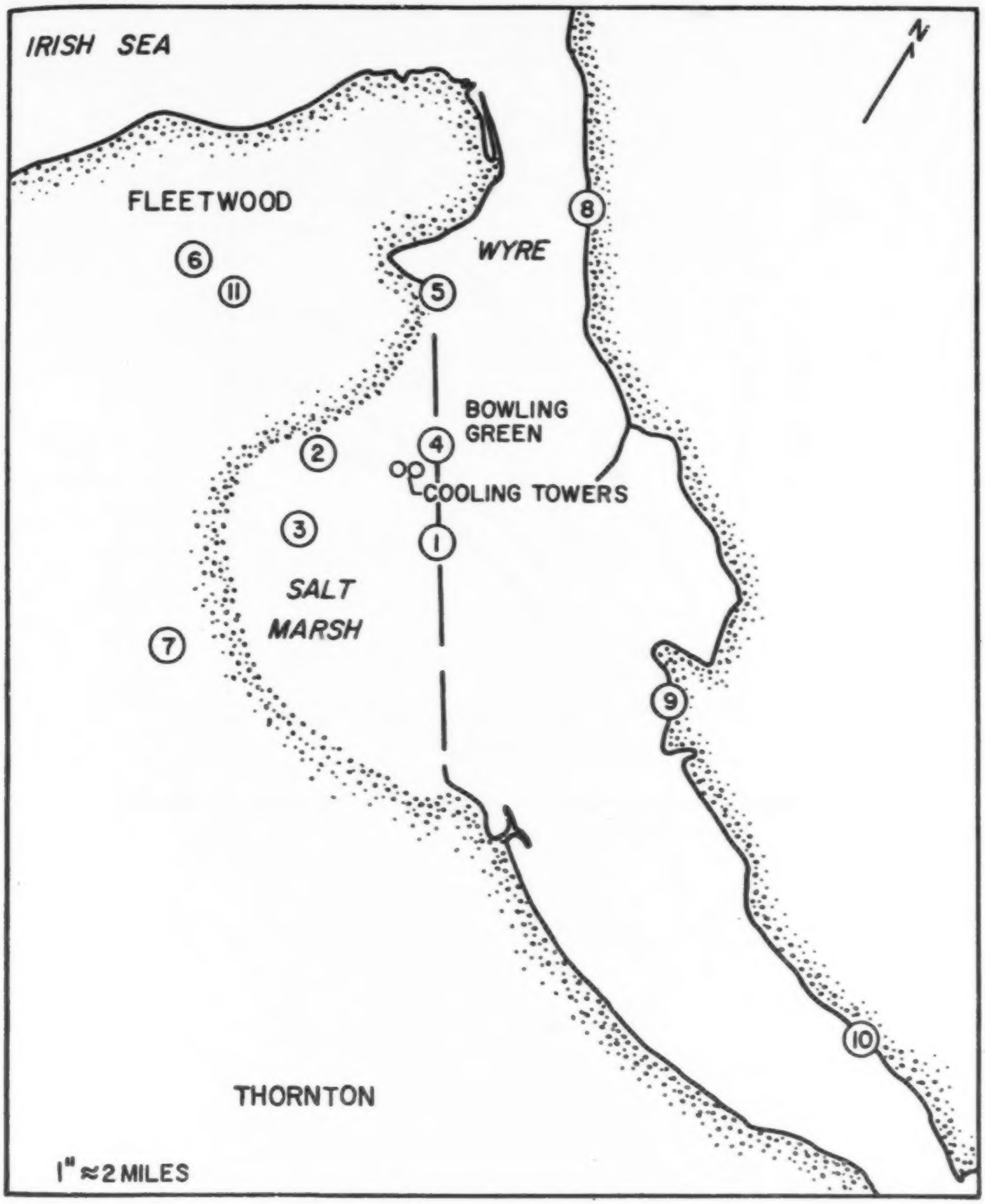


Figure 4-23 Layout Of Deposit Gauges In Vicinity Of Fleetwood Power Station (1)

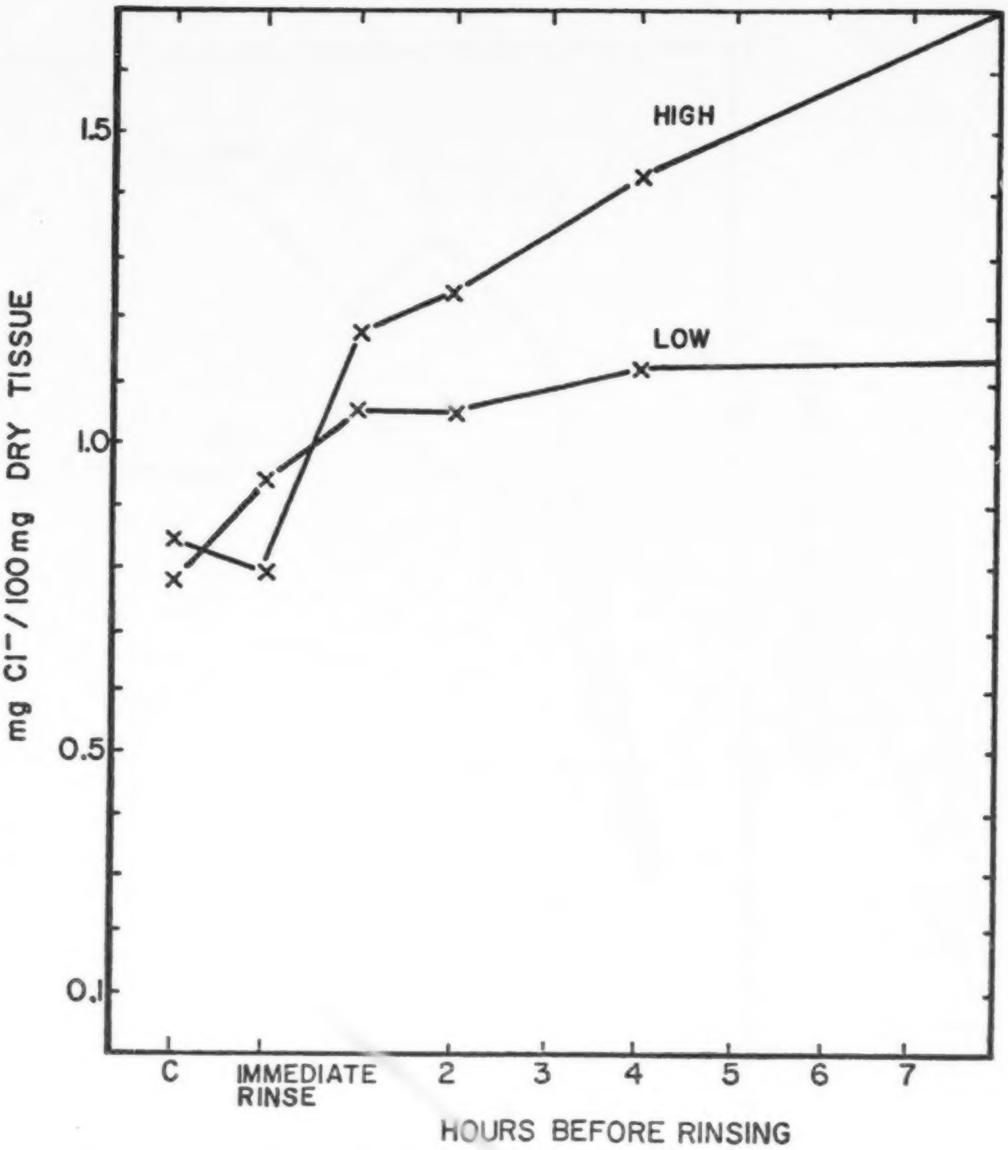


Figure 4-24 Chloride buildup in bush bean leaf tissue over 8 hours from one spray application in each of two humidity conditions. High humidity - 75-80% RH; low humidity - 55-70% RH. Control plants (C) were not sprayed (31)

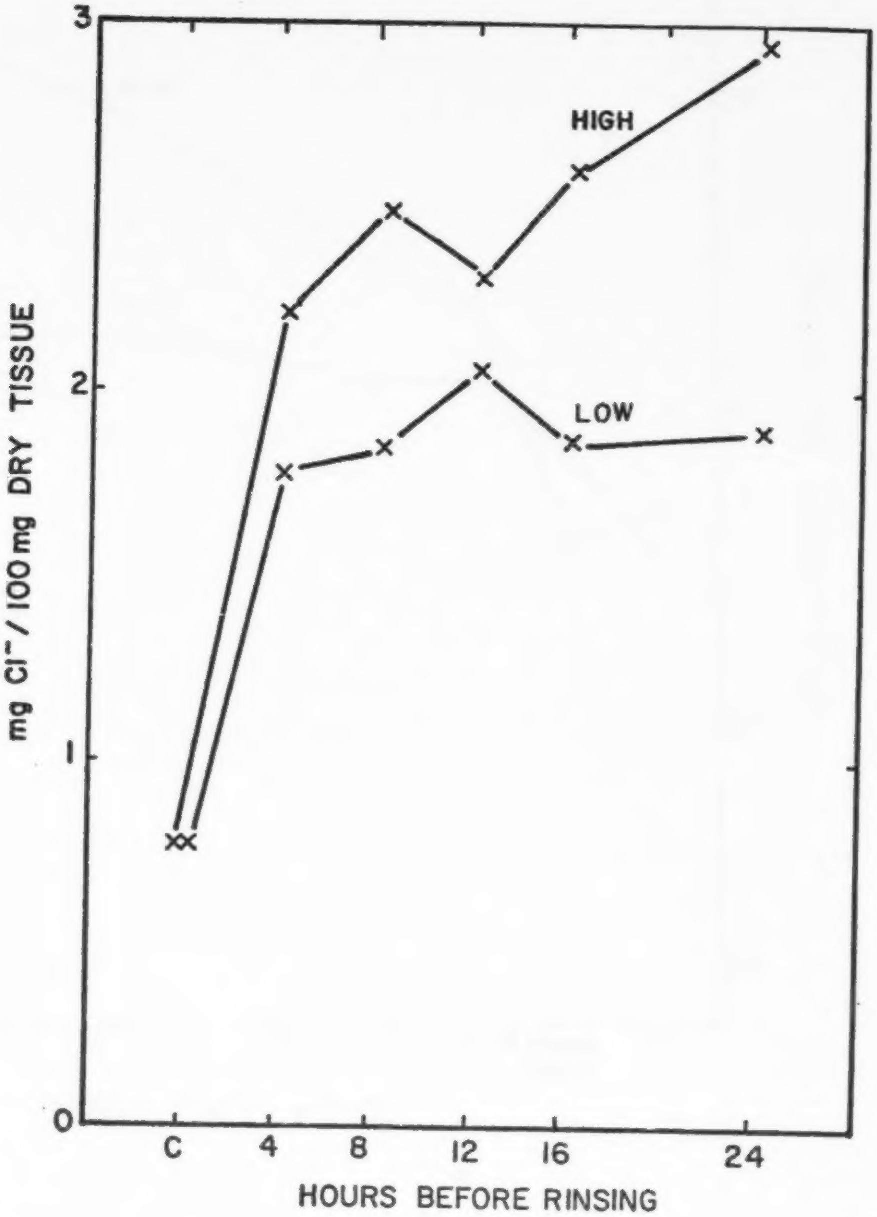


Figure 4-25 Chloride buildup in bush bean leaf tissue over 24 hours from one spray application in each of two humidity conditions. High humidity - 75-80% RH; low humidity - 55-70% RH. Control plants (C) were not sprayed (31)

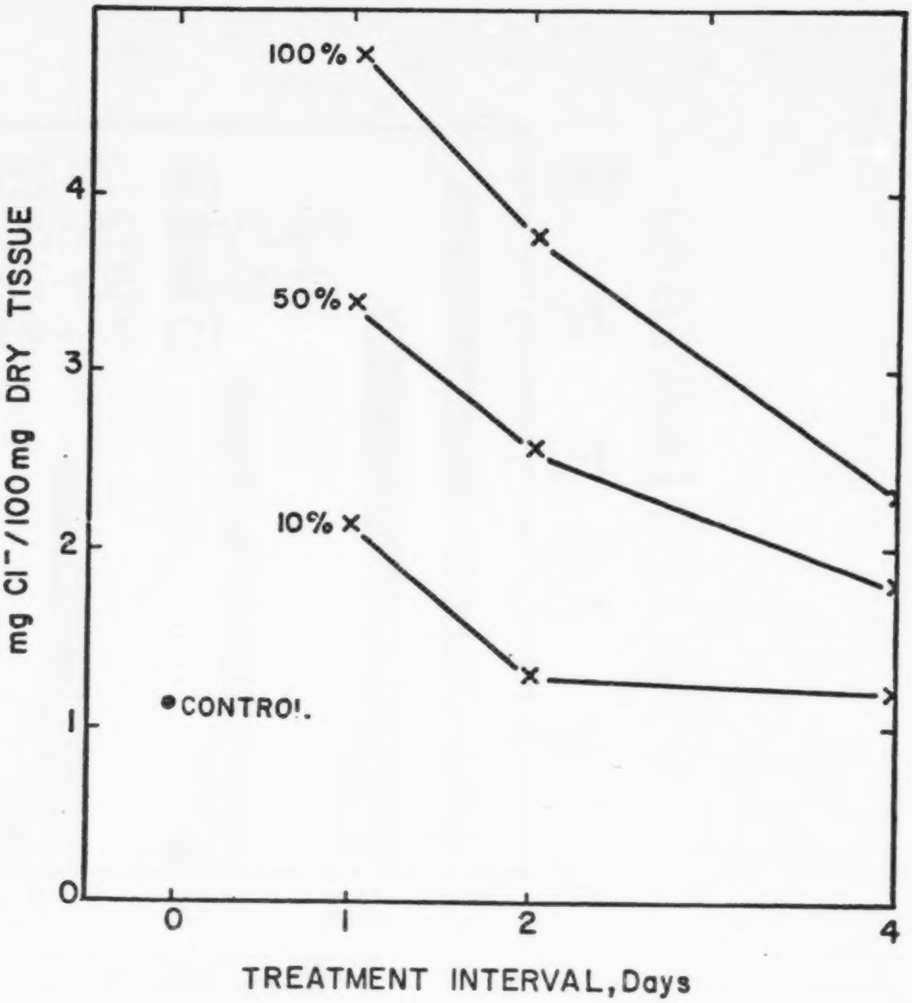


Figure 4-26 Chloride accumulation in bush bean foliage tissue over a period of one month after one spraying per treatment at indicated intervals with 10, 50 or 100% sea water (31)

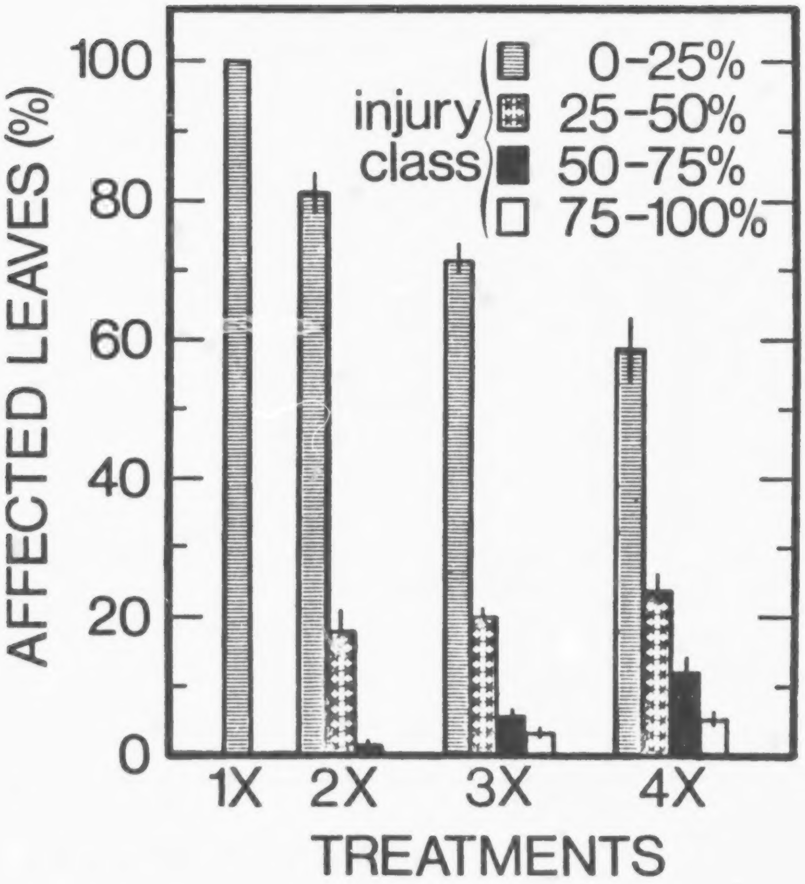
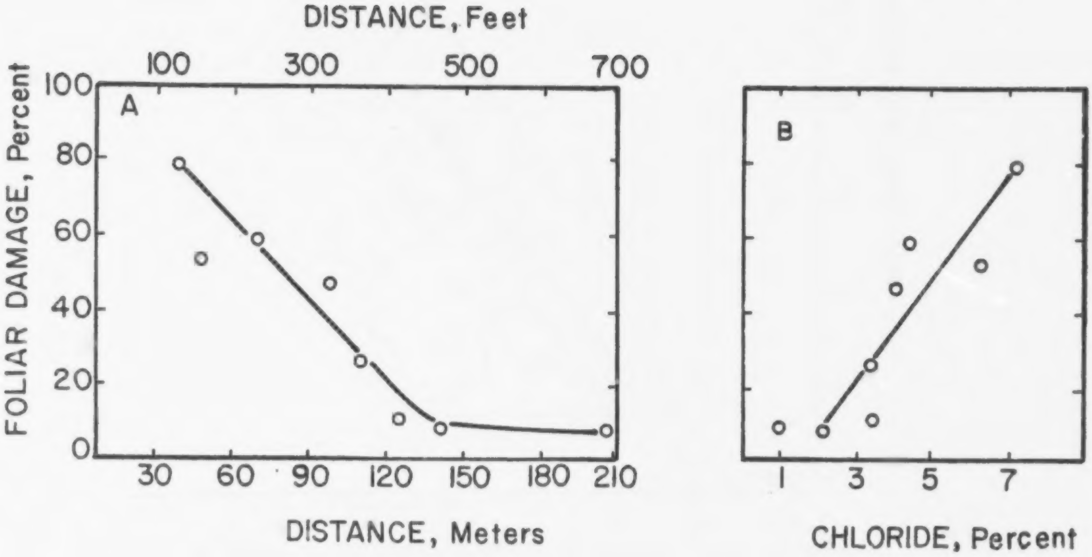


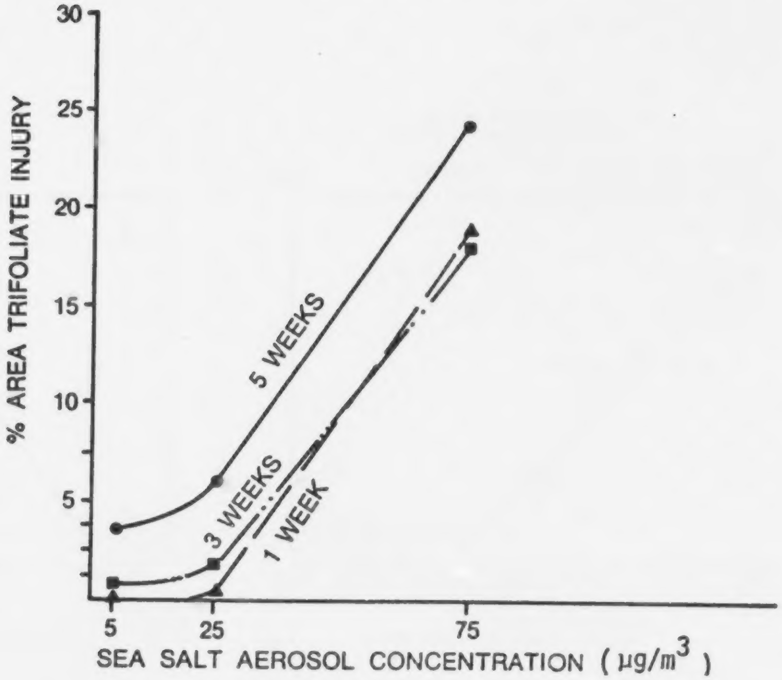
Figure 4-27 Dogwood leaf injury classes after simulated drift treatment (21)



(A) Distance from the roadside, and

(B) Foliar concentration of chloride

Figure 4-28 Foliar damage of red pine (Pinus resinosa) (42)



(Exposure initiated at: —●— 5 weeks, —■—, 3 weeks, ---▲---, 1 week.)

Figure 4-29 Mean percentage foliar area injured on the first three sets of trifoliate leaves of three ages of bush bean (Phaseolus vulgaris L.) after 100 hours exposure to various sea salt aerosol concentrations (27)

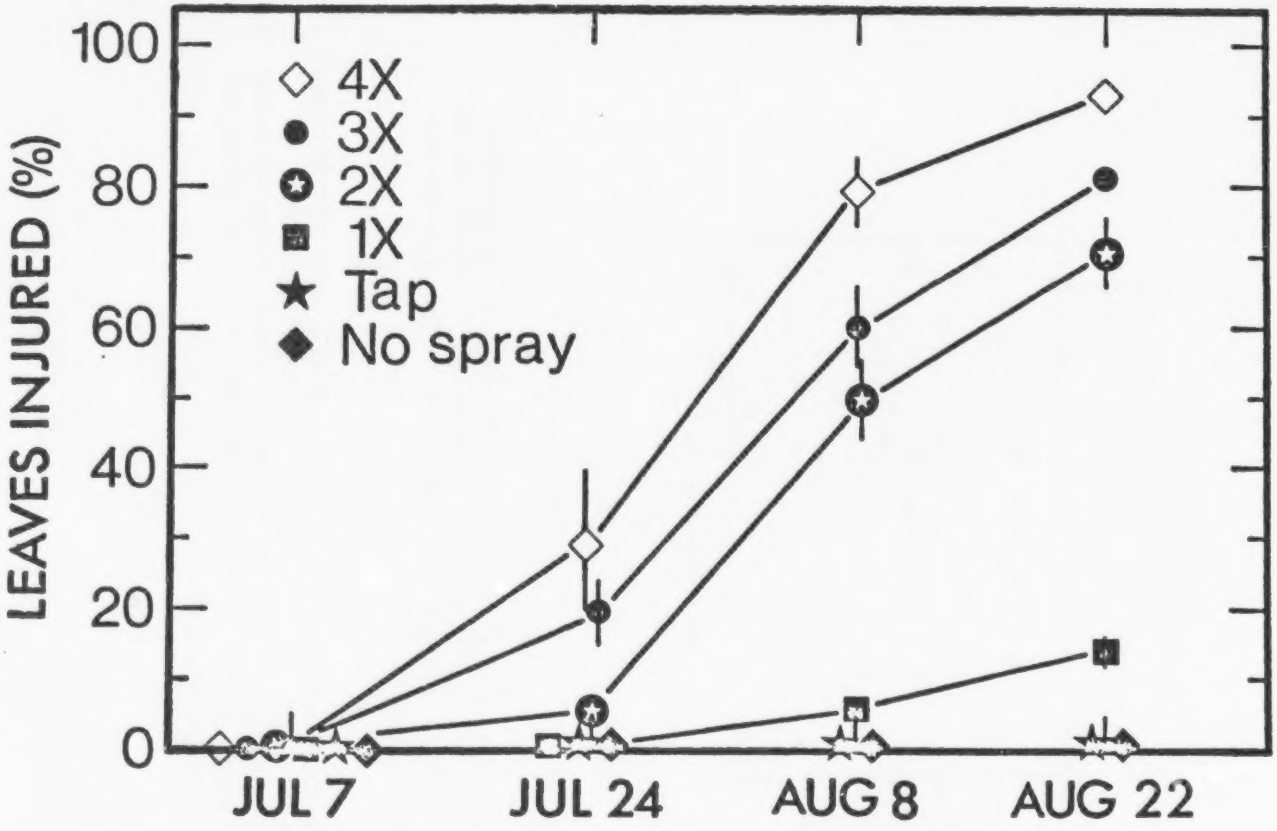
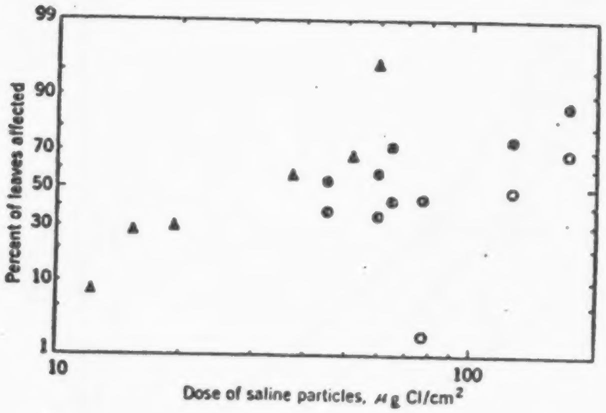


Figure 4-30 Dogwood leaf injury classes after simulated drift treatment (23)



LEGEND

▲ exposures to 85% relative humidity (RH) to an aerosol with 56, 28, and 04-13% of the particles between 50 and 150, between 150 and 250, and greater than 250 microns diameter, respectively.

○ exposures to an aerosol with 95% of the particles between 50 and 150 microns in diameter and 0-85% RH during and after exposure; 0-50% RH during and after exposure; 0-85% RH during, 50% RH after exposure; and 0-50% RH during and 85% RH after exposure.

Figure 4-31 Relationship between incidence of foliar injury in bush bean and dose of saline aerosol (24)

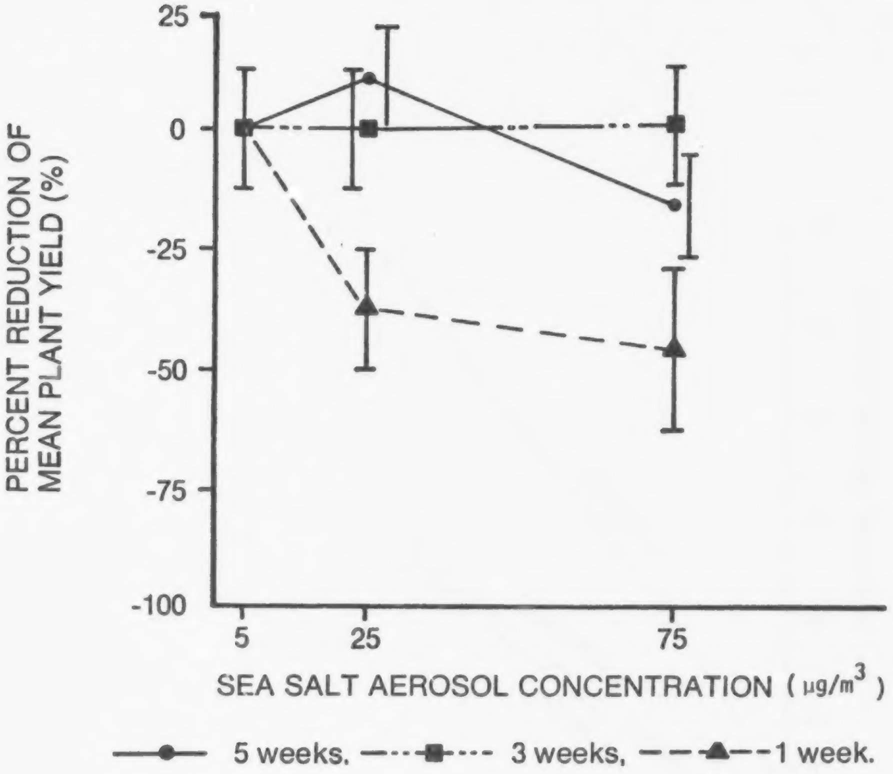


Figure 4-32 Percentage reduction of mean plant pod dry weight (with seeds) of mature bush bean after exposure to three different sea salt aerosol concentrations at three stages of growth (plant age at initiation of exposure) (27)

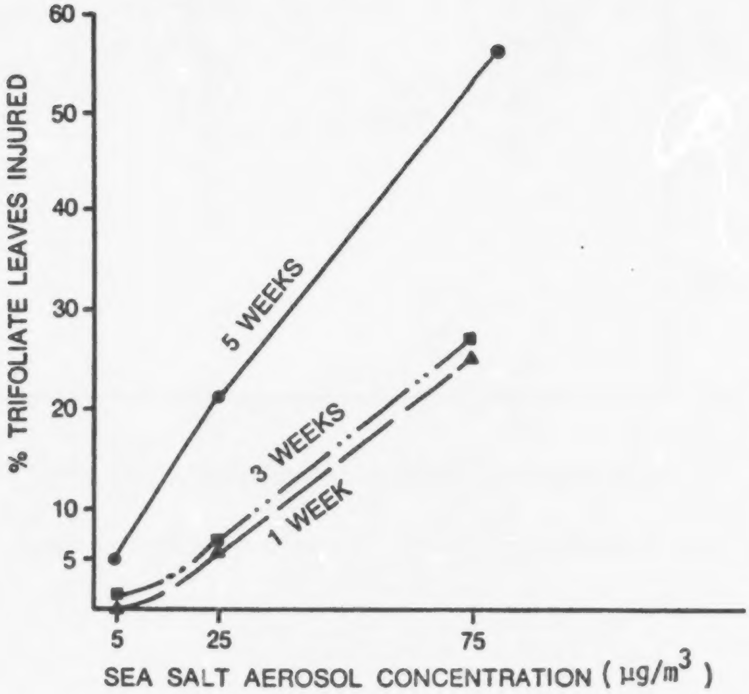
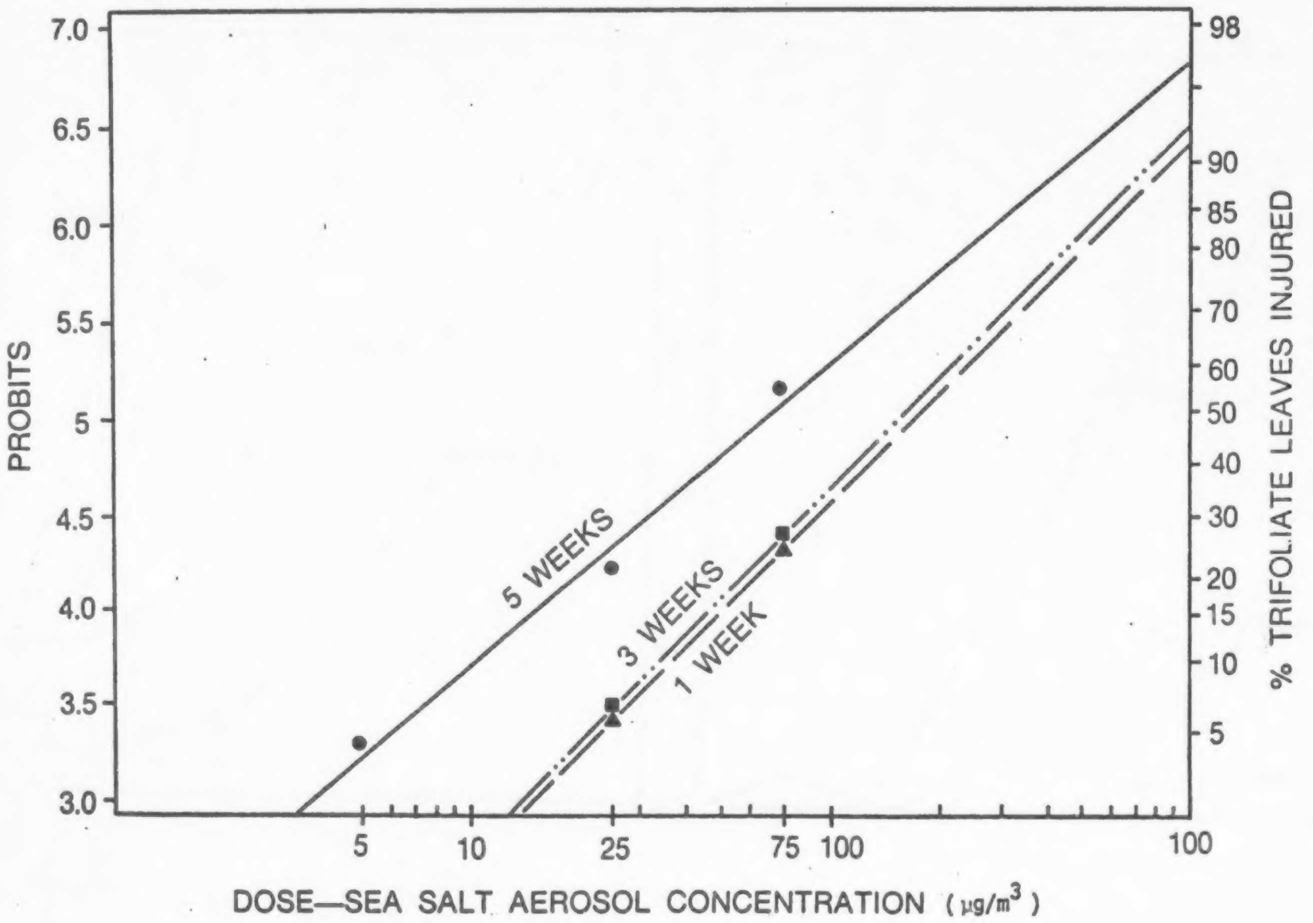


Figure 4-33 Mean percent trifoliate leaves injured on three ages of bush bean (*Phaseolus vulgaris* L.) after 100 hours exposure to different sea salt aerosol concentrations (27)

Figure 4-34 Log dose-response plot for bush bean(*Phaseolus vulgaris* L.) trifoliate leaves injured following exposure to three concentrations of sea salt aerosol for 100 hours at different stages of growth. ED^{50} represents the concentration where 50% of all trifoliate leaves exhibit injury (27)



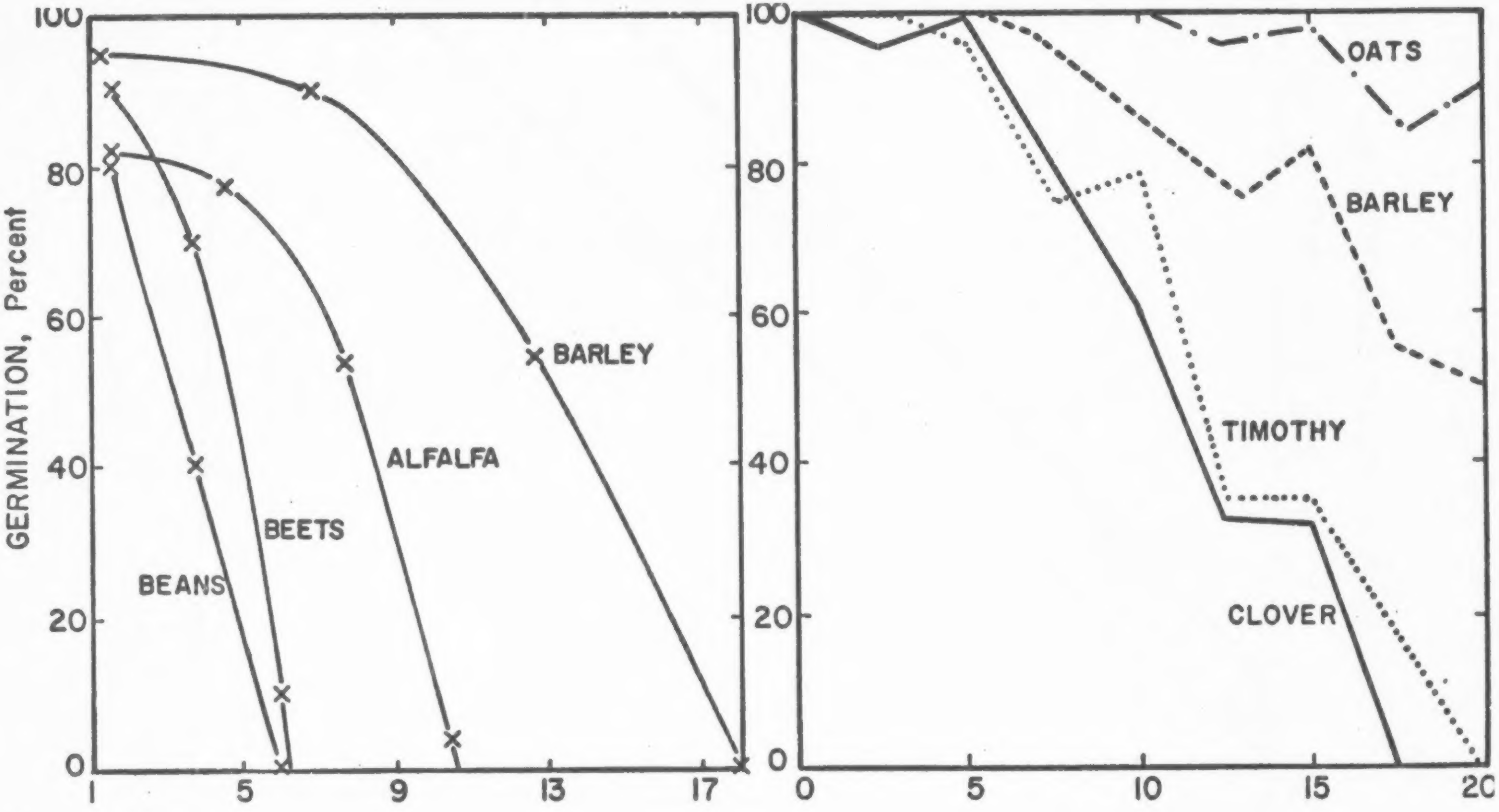


Figure 4-35 Effect of soil salinity on germination of crop plants (1)

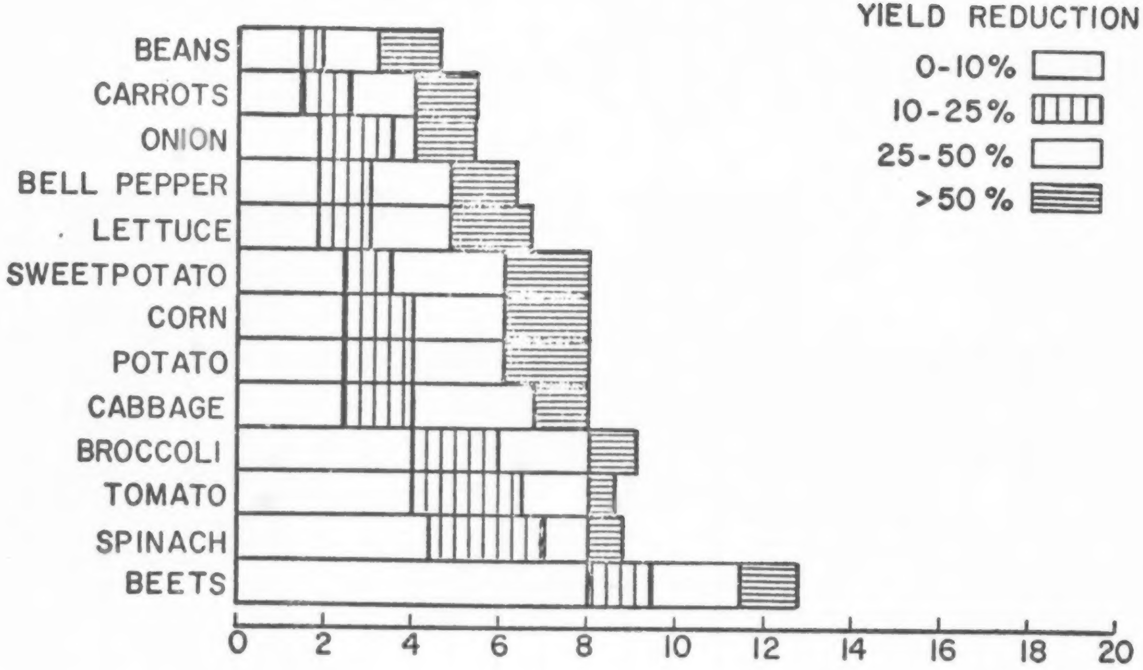


Figure 4-36 Salt tolerance of vegetable crops grown from late seedling stage to maturation. Crops are arranged in order of increasing salt tolerance (1)

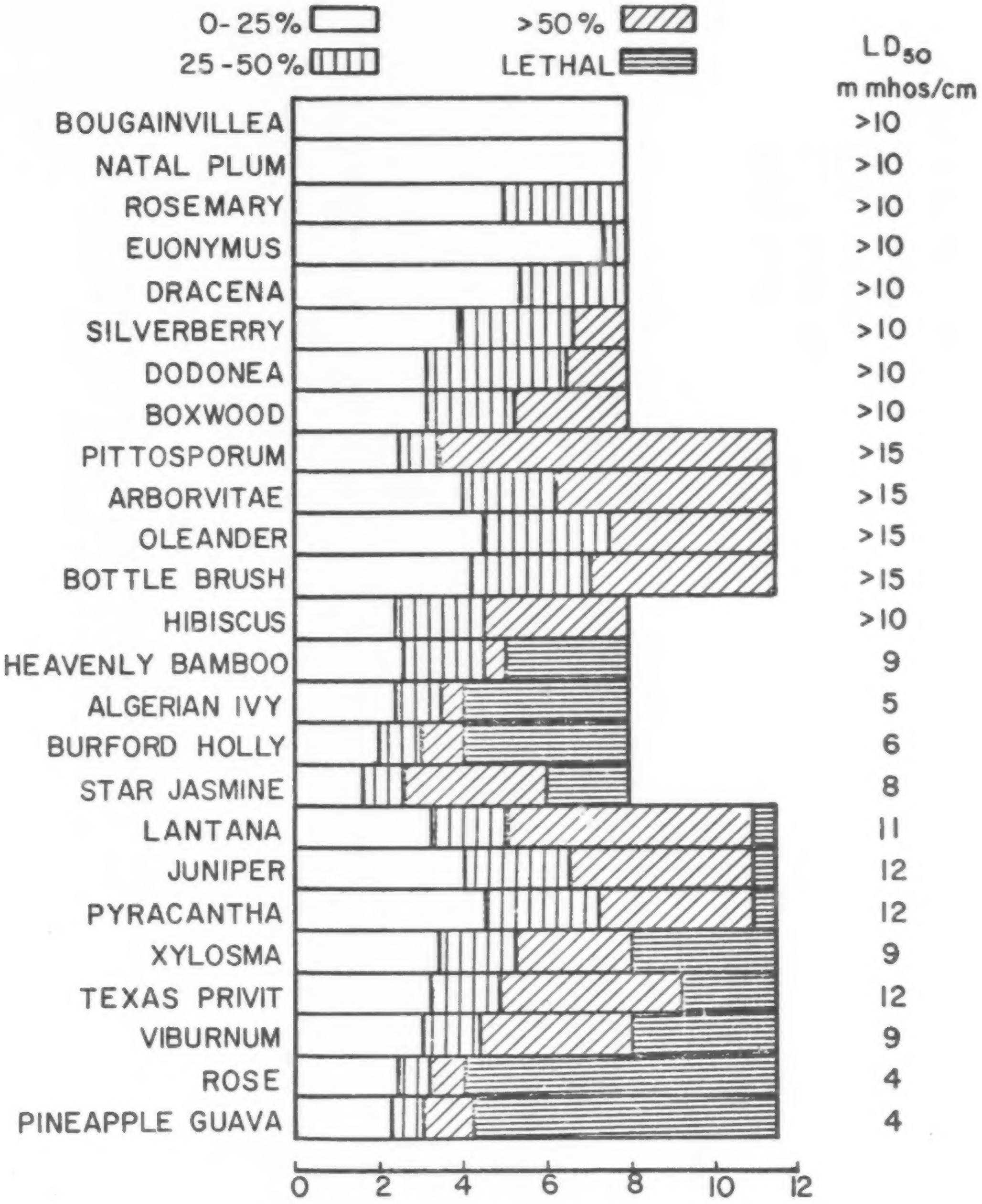


Figure 4-37 Salt tolerance of ornamentals as measured by the decrease of top-growth weight. The estimated soil salinities at which 50% of the specimens of each species died are indicated as LD_{50} (36)

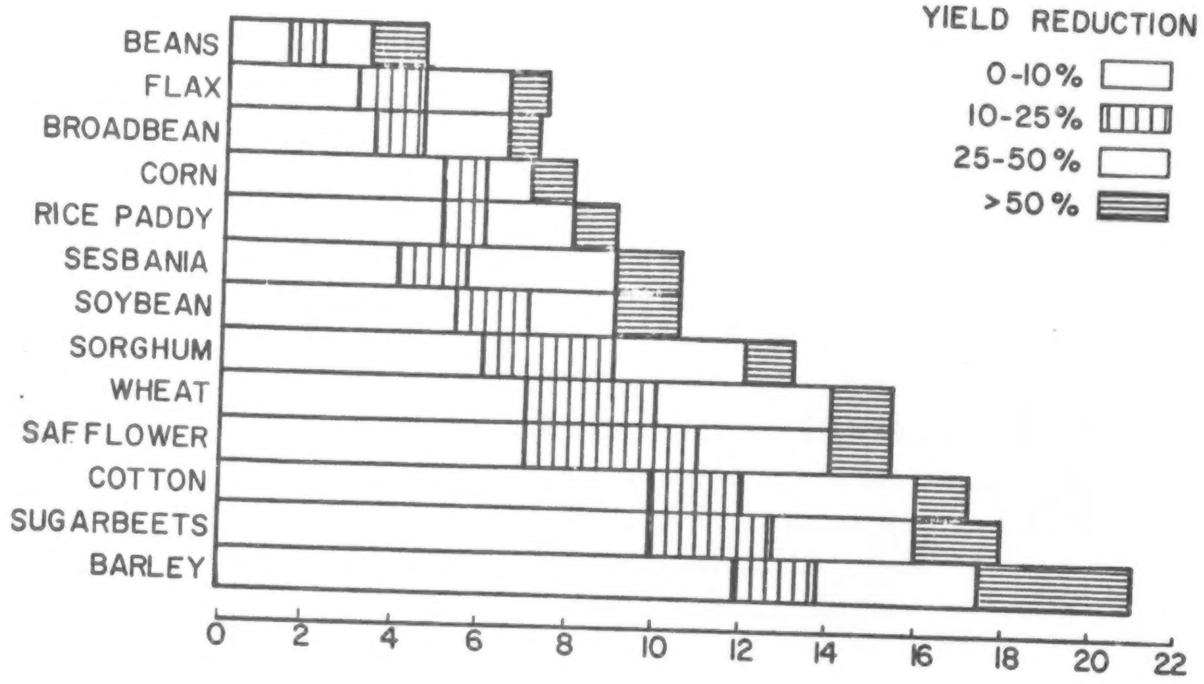


Figure 4-38 Salt tolerance of yield crops grown from late seedling stage to maturation. Crops are arranged in order of increasing salt tolerance (1,55)

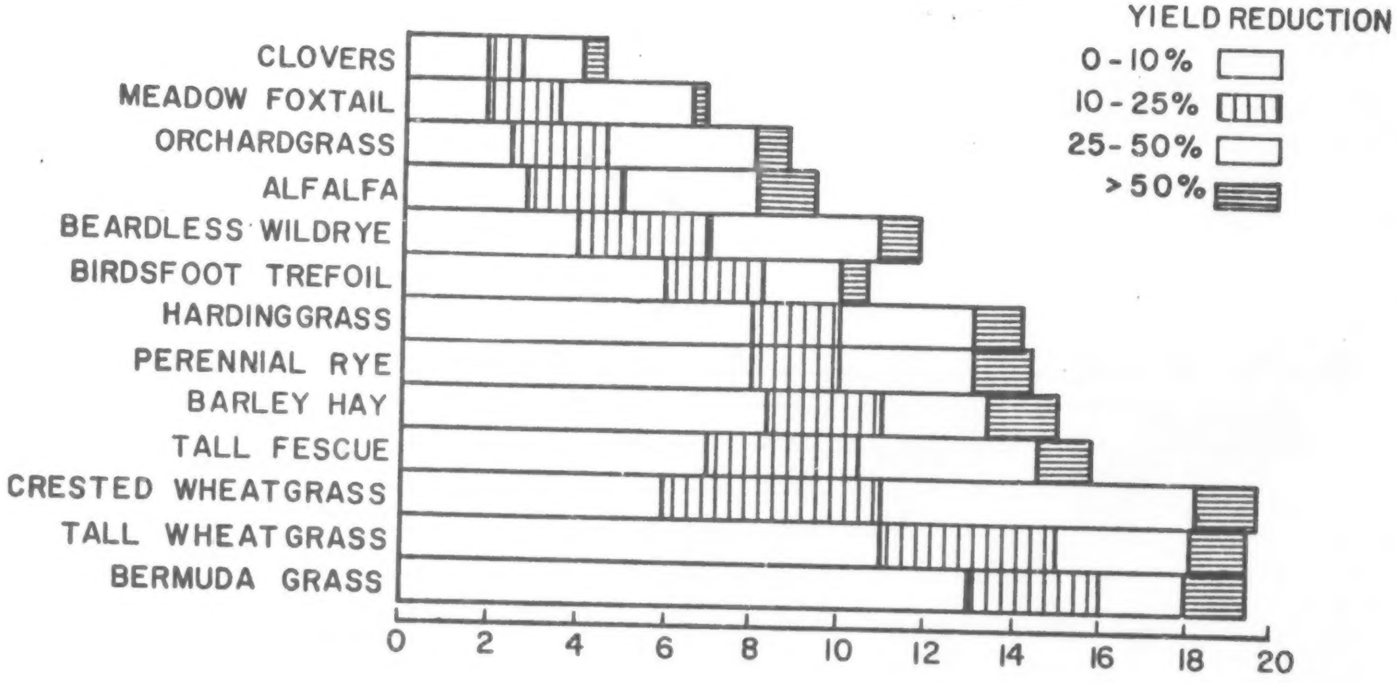


Figure 4-39 Salt tolerance of forage crops grown from late seedling stage to maturation. Crops are arranged in order of increasing salt tolerance (55)

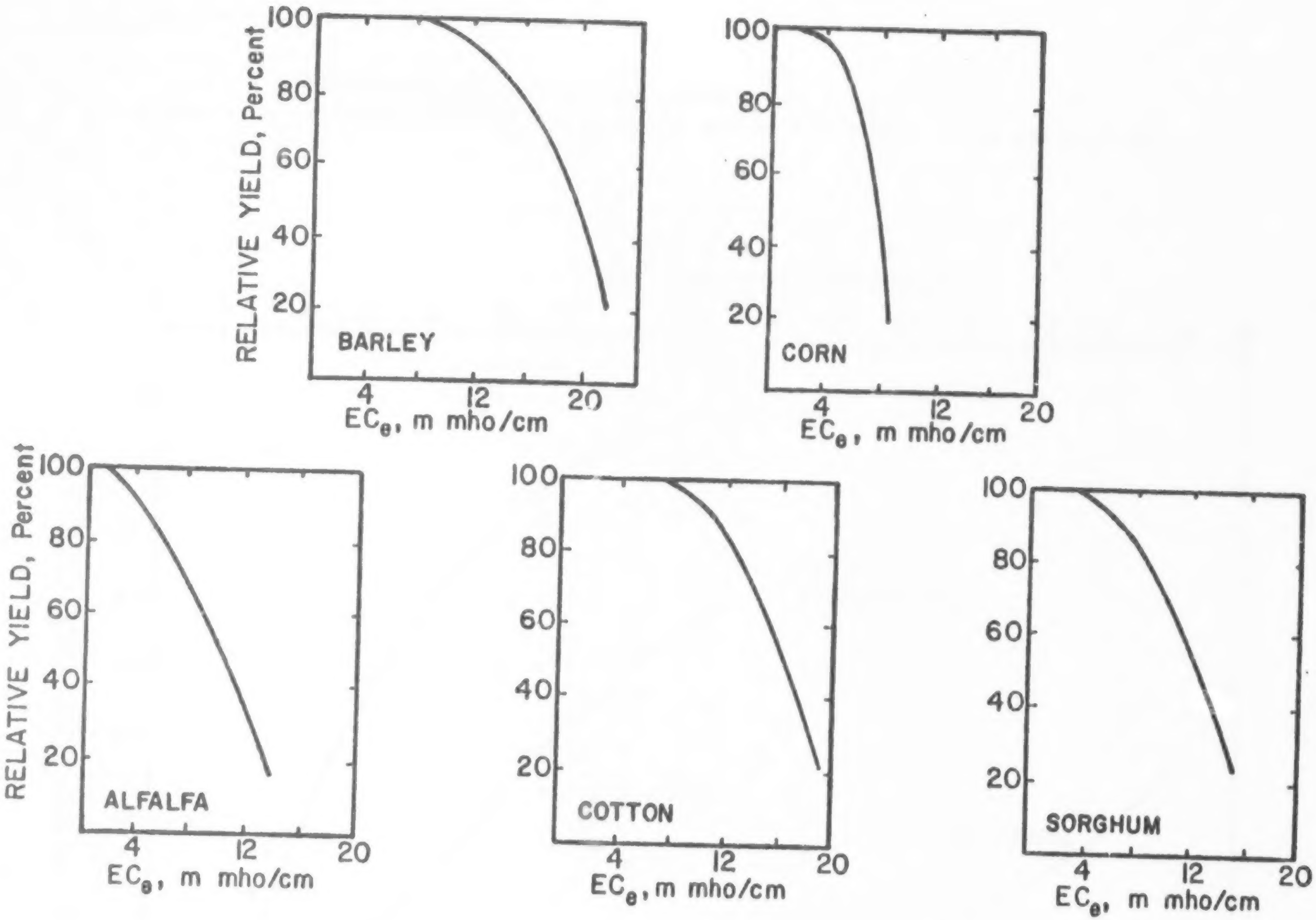


Figure 4-40 Relation between soil salinity and relative yield of five crop plants (1)

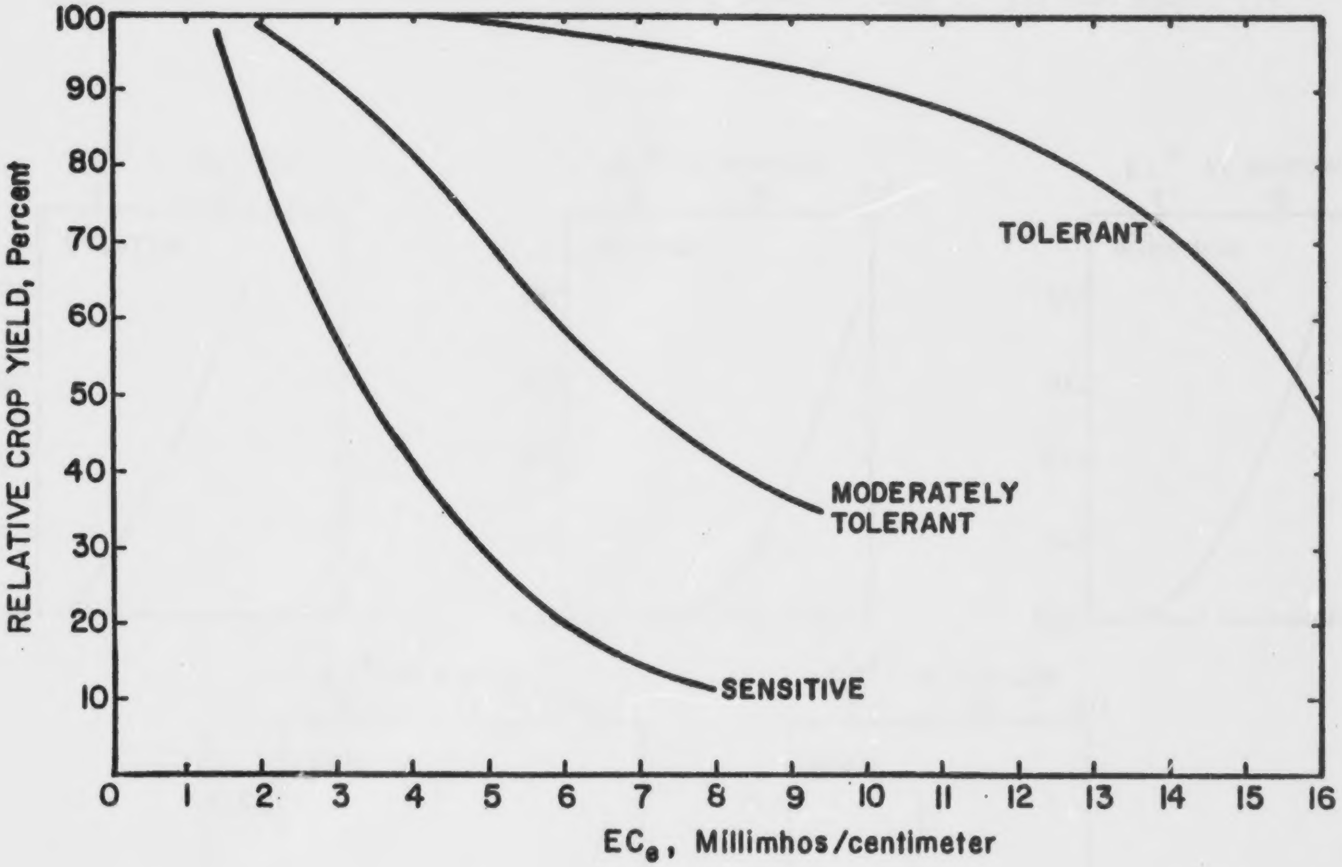


Figure 4-41 Relation between Soil Salinity and Relative Crop Yield for Tolerant, Moderately Tolerant and Sensitive Plant (1,49)

TABLE 4-1

EFFECTS OF SIMULATED RAIN ACIDIFIED WITH SULFURIC ACID ON HOST-PARASITE INTERACTIONS

(56)

Host-Pathogen System	Acidity of Simulated Rain			Disease Measure	
	Pre-Inoculation (pH)	Inoculation (pH)	Post-Inoculation (pH)		
Greenhouse Studies				Infected Leaves/ Plant	Telia/ Infected Leaf*
Quercus phellos-Cronartium fusiforme Oak-Pine Rust of Oak	3.2	3.2	3.2	3.8+	15+
	6.0	6.0	6.0	6.5	115
Phaseolus vulgaris-Pseudomonas phaseolicola				Dead Leaflets/ Plant‡,§ (No.)	
Halo Blight of Bean	3.2	3.2	3.2	0.0a#	
	3.2	3.2	6.0	0.0a	
	3.2	6.0	3.2	4.2d	
	3.2	6.0	3.2	4.8d	
	6.0	3.2	3.2	0.0a	
	6.0	3.2	6.0	0.0a	
	6.0	6.0	3.2	2.0b	
	6.0	6.0	6.0	3.2c	
			LSD .05	0.77	

*ANOVA significant, $p = 0.05$

+Each value is the mean of 6 plants/treatment

‡No. of inoculated leaflets (max. 6/plant) which were dead on plants which developed symptoms characteristic of halo blight

§Each value is the mean of 5 plants.

#Values in a column followed by the same letter were not significantly different, $LSD_{.05}$.

TABLE 4-1 (cont'd)

EFFECTS OF SIMULATED RAIN ACIDIFIED WITH SULFURIC ACID ON HOST-PARASITE INTERACTIONS

(56)

Host-Pathogen System	Acidity of Simulated Rain Pre-Inoculation (pH)	Inoculation (pH)	Post-Inoculation (pH)	Disease Measure	
Field Studies				Eggs/Plant[+]	% Root Galled[+,‡]
Phaseolus vulgaris-*Meloidogyne hapla* Root Knot Nematode on Beans	3.2	3.2	3.2	74*	26
	6.0	6.0	6.0	217	50
				% Leaf Area Affected At: 7 Weeks	9 Weeks
Phaseolus vulgaris-*Uromyces phaseoli* Rust of Beans	3.2	3.2	3.2	22*	48
	6.0	6.0	6.0	31	45

[*] ANOVA significant, $p = 0.05$

+Each value is the mean of 18 plants/treatment.

‡Percent of root area galled by *Meloidogyne hapla*.

TABLE 4-2

OVERALL COLLECTION EFFICIENCY FOR DIFFERENT TYPES OF DRIFT ELIMINATORS (1)

Case No.	Eliminator Type	Pitch,cm	Height,cm	Inclination Angle, °	Air Flow m/sec	Calculated Overall Collection Efficiency
1	Single louver	3.92	5.44	45	0.91	0.9284
2		3.92	5.44	45	1.52	0.9816
3		3.92	5.44	45	2.13	0.9987
4		6.2	13.2	60	2.13	0.7978
5		4.4	14.7	75	1.52	0.7516
6	Double-layer louvers	4.25	13.2	60	0.91	0.9580
7		----	----	--	1.52	0.9762
8		----	----	--	2.13	0.9576
9	Sinus shape	5.08	17.8	--	2.13	0.9992

TABLE 4-3

FACTORS AFFECTING DISPERSION AND DEPOSITION OF DRIFT FROM NATURAL-DRAFT AND MECHANICAL-DRAFT TOWERS (1)

Factors associated with the design and operation of the cooling tower	Factors related to atmospheric conditions	Other factors
Volume of water circulating in the tower per unit time	Atmospheric conditions including humidity, wind speed and direction, temperature, Pasquill's stability classes, which affect plume rise, dispersion and deposition.	Adjustments for non-point source geometry
Salt concentration in the water		Collection efficiency of ground for droplets
Drift rate		
Mass size distribution of drift droplets	Tower wake effect which is especially important with mechanical draft towers	
Moist plume rise influenced by tower diameter, height and mass flux	Evaporation and growth of drift droplets as a function of atmospheric conditions and the ambient conditions	
	Plume depletion effects	

TABLE 4-4

ATMOSPHERIC VARIABLES AND CHARACTERISTICS AFFECTING THE DISPERSION AND THE DEPOSITION OF DRIFT (60)

Atmospheric variables	Atmospheric characteristics
Ambient temperature	Atmospheric stability
Ambient relative humidity	Depth of the mixing layer
Wind speed and direction	
Precipitation (rain and snow)	
Concentration of condensation nuclei	

TABLE 4-5

DESIGN AND OPERATION CHARACTERISTICS OF WET COOLING SYSTEMS AFFECTING THE DRIFT RATES (60)

Cooling towers	Spray canals or ponds
Volume of circulating water in the system per unit time	Volume of circulating water in the system per unit time
Tower features (height, diameter, and characteristics of drift eliminators for natural-draft tower; height, cell diameter, characteristics of drift eliminators, and number of cells for mechanical draft tower)	Area, spray modules spacing, and spray nozzle characteristics (droplets size and spray pattern)
Drift flux and droplets size distribution	Drift flux and droplets size distribution
Exit temperature	Spray nozzles exit temperature
Efflux velocity	Spray nozzles exit velocity

TABLE 4-6

SUMMARY OF DRIFT RATE AND DROPLET SIZE DISTRIBUTION MEASUREMENT TECHNIQUES (1)

Method	Measurement Capacity		Field Application	Accuracy			Maintenance	Cost
	Drift Rate	Droplet Size Distribution		Calibration	Interpretation Result			
					Drift Rate	Particle Size		
Sensitive paper	yes	yes	good	fair	fair	fair	none	low
Coated slides	yes	yes	fair	fair	fair	fair	none	low
Impaction	yes	no	good	good	good	-	small	fair
Cyclone Separator	yes	no	good	good	good	-	small	high
Light Scattering	yes	yes	fair	good	good	very good	moderate	high
High-Volume Sampling	yes	no	good	good	fair	fair	small	low
Chemical Balance	yes	no	fair	none	fair	-	none	fair
Calorimetry	yes	no	fair	good	fair	-	small	fair

TABLE 4-7

WINDROSE DATA FOR DEPOSITION AT ATLANTIC CITY (5)

Unit Operation: On During Entire Test Period

Station Number	1	2	3	9	4	8	5	6
Wind Direction NNE								
Average Deposition	823.7	116.4	453.5	66.3	63.0	135.4	36.1	96.4
Entries	3.	2.	3.	3.	1.	2.	2.	1.
Wind Direction NE								
Average Deposition	0.0	0.0	0.0	1810.2	0.0	0.0	0.0	0.0
Entries	0.	0.	0.	1.	0.	0.	0.	0.
Wind Direction ENE								
Average Deposition	1336.0	428.7	563.6	481.5	215.3	623.1	0.0	0.0
Entries	1.	1.	1.	1.	1.	1.	1.	1.
Wind Direction E								
Average Deposition	1626.9	394.5	311.7	0.0	883.6	677.1	1215.0	716.2
Entries	1.	1.	1.	0.	1.	1.	1.	1.
Wind Direction ESE								
Average Deposition	1098.6	213.1	383.5	386.2	177.0	124.0	3837.5	0.0
Entries	7.	5.	7.	7.	4.	9.	4.	0.
Wind Direction SE								
Average Deposition	979.3	389.4	581.9	60.0	115.9	91.3	369.5	69.4
Entries	8.	6.	2.	3.	8.	7.	3.	9.
Wind Direction SSE								
Average Deposition	2186.6	1089.4	1222.4	116.4	356.9	115.8	324.0	77.4
Entries	9.	10.	12.	11.	8.	6.	13.	8.
Wind Direction S								
Average Deposition	1943.8	861.8	435.3	441.4	155.2	308.7	42.3	71.0
Entries	8.	8.	6.	6.	8.	5.	3.	8.

TABLE 4-7 (cont'd)

Station Number	1	2	3	9	4	8	5	6
Wind Direction SSW								
Average Deposition	412.5	695.8	182.2	48.3	17.5	153.5	80.2	26.6
Entries	3.	4.	4.	4.	3.	2.	2.	3.
Wind Direction SW								
Average Deposition	594.6	123.9	83.9	89.5	53.3	73.6	5844.5	77.3
Entries	--	--	--	--	--	--	--	--

TABLE 4-8

WINDROSE DATA FOR DEPOSITION AT ATLANTIC CITY (5)

Station Number	1	2	3	9	4	8	5	6
Wind Direction WSW								
Average Deposition	498.6	230.9	45.1	42.8	51.5	41.7	62.9	25.7
Entries	9.	10.	9.	9.	5.	5.	4.	3.
Wind Direction W								
Average Deposition	1077.5	38.3	40.4	54.7	553.6	100.3	304.8	40.7
Entries	2.	2.	2.	2.	2.	3.	1.	2.
Wind Direction WNW								
Average Deposition	186.2	23.0	374.8	56.0	73.2	40.0	660.0	23.4
Entries	2.	2.	4.	5.	7.	6.	8.	7.
Wind Direction NW								
Average Deposition	285.5	67.1	80.2	34.9	32.5	20.9	257.4	151.9
Entries	6.	6.	7.	4.	2.	2.	4.	9.
Wind Direction NNW								
Average Deposition	510.8	103.3	51.9	208.6	115.4	161.2	27.7	36.8
Entries	2.	2.	2.	3.	3.	4.	2.	5.
Wind Direction N								
Average Deposition	2420.0	198.2	71.2	75.2	60.7	0.0	0.0	0.0
Entries	2.	1.	1.	1.	1.	0.	0.	0.
Cumulative Average	1126.2	459.9	433.9	183.6	165.9	134.4	729.4	81.4
Total Entries	65.	62.	62.	61.	57.	56.	48.	60.

TABLE 4-9

OBSERVED DEPOSITION AT CHALK POINT (7)

# drops/m^2-hr

6/17

Distance (m)	Direction	OBS
240	213	1646
610	221	605
620	211	288
710	213	1119
870	210	394

6/18
AM

Distance (m)	Direction		OBS
260	222		4289
610	249		4745
620	212		6487
740	208		3704
1040	203		4834
	PM		
240	170		
300	149		
		Totals	3601
380	183		
460	151		
		Totals	808
520	182		
590	146		
		Totals	921
770	182		
990	165		
		Totals	6226
990	182		
990	167		
		Totals	219

TABLE 4-9 (cont'd)

6/19

Distance (m)	Direction	OBS
240	145	4200
370	178	3390
440	173	3113
440	183	6714
460	164	4419

6/22

Distance (m)	Direction	OBS
240	188	3711
390	188	2339
570	192	5121
770	183	2393

6/23

Distance (m)	Direction		OBS
180	230		
180	174		
		Totals	10803
320	90		3125
380	174		
490	219		
		Totals	120
540	173		
620	214		
		Totals	37

TABLE 4-9 (cont'd)

6/24

Distance (m)	Direction	OBS
270	220	2597
320	90	10822
630	205	2583
630	218	715
650	212	167

TABLE 4-10

COMPARISON OF TYPICAL DRIFT DROPLET MEASUREMENTS (8)

Traverse Number	MMD (μm)	
	PMS	Film
15-2	80	329
15-3	80	371
15-4	40	315
15-5	280	329
15-6	200	343
15-7	80	287
15-8	140	399
15-10	100	231
15-11	40	231
15-12	80	343
15-13	280	273

TABLE 4-11

COOLING TOWER COMPOSITE DRIFT MASS EMISSION PARAMETERS (9)

d(center) (μm)	Δd (μm)	Composite Drift Flux (μg/m²·s)	$\Delta X_i/\Delta d$ (μg/m³·μm)	Composite Drift Mass Emission Rate, ΔD_i (μg/s)
20	20	590	29.5	2.78E 05
40	20	881	44.1	4.14E 05
65	30	1,205	40.2	5.61E 05
95	30	958	31.9	4.40E 05
130	40	987	24.7	4.46E 05
175	50	867	17.3	3.82E 05
225	50	600	12.0	2.57E 05
275	50	378	7.6	1.58E 05
325	50	287	5.7	1.16E 05
375	50	240	4.8	9.41E 04
425	50	219	4.4	8.37E 04
475	50	185	3.7	6.89E 04
525	50	171	3.4	6.12E 04
575	50	168	3.4	5.83E 04

Note: 2.78E 05 means 2.78×10^5

TOTAL COMPOSITE DRIFT FLUX = 7,736 μg/m²·s

TOTAL COMPOSITE DRIFT MASS EMISSION RATE = .3.42 gm/s

MASS MEDIAN DIAMETER of the composite drift mass density distribution, $\Delta X_i/\Delta d$ = 120 μm

COMPOSITE TOWER DRIFT FRACTION (based on the design flow rate of 1260 kg/s) = 0.00027%

TABLE 4-12

RATES OF SODIUM AND MAGNESIUM MASS EMISSION FROM THE TURKEY POINT COOLING TOWER (9)

	Fan Stack Exit Diameter Traverse				
	SW-NE 1	SW-NE 2	SW-NE 3	NW-SE 1	NW-SE 2
Weighted Average Sodium Basin Water Concentration per Traverse, mg/1	7,390	11,430	10,720	9,545	11,540
Weighted Average Magnesium Basin Water Concentration per Traverse, mg/1	845	1,165	1,220	1,005	1,170
Rate of Sodium Emission, μg/sec	67,000	143,630	123,150	72,860	89,550
Rate of Magnesium Emission, μg/sec	7,680	14,350	13,880	8,120	9,370
Rate of Sodium Circulating as Solute in the Basin Water, μg/sec	8.86×10^{9}	1.37×10^{10}	1.04×10^{10}	1.14×10^{10}	1.38×10^{10}
Rate of Magnesium Circulating as Solute in the Basin Water, μg/sec	1.01×10^{9}	1.40×10^{9}	1.18×10^{9}	1.20×10^{9}	1.40×10^{9}
Sodium Mass Emission Fraction, %	0.00076	0.00105	0.00118	0.00064	0.00065
Magnesium Mass Emission Fraction, %	0.00076	0.00103	0.00118	0.00068	0.00067
Salt Mass Emission Fraction, %	0.00076	0.00104	0.00118	0.00066	0.00066
Adjusted Rate of Sodium Emission, μg/sec	88,200	122,100	111,700	74,200	75,500
Adjusted Rate of Magnesium Emission, μg/sec	9,600	13,000	12,000	8,540	8,430

The adjusted rates of sodium and magnesium emission belong to sodium and magnesium basin water concentrations of 9720 mg/1 and 1055 mg/1, respectively, which are the average values for the test duration.

TABLE 4-13

REPRESENTATIVE DRIFT EMISSION DATA OF THE TURKEY POINT COOLING TOWER (9)

Droplet Diameter Intervals			Drift Emission in Percent of Total
d' μm	d'' μm	Δd μm	
10	30	20	7.80
30	50	20	11.18
50	80	30	14.96
80	110	30	11.68
110	150	40	11.85
150	200	50	10.20
200	250	50	6.56
250	300	50	4.23
300	350	50	3.11
350	400	50	2.53
400	450	50	2.22
450	500	50	1.82
500	550	50	1.61
550	600	50	1.53
600	700	100	0.33
700	2250	1550	8.39

Total Drift Emission Rate:	3.979 g/sec	(2.584 g/sec)
Mass Median Diameter:	125 μm	
Water Flow Rate:	1154 kg/sec	
Drift Fraction:	0.00034%	(0.00056%)
Sodium Emission Rate:	94,340 μg/sec	(21,600 μg/sec)
Magnesium Emission Rate:	10,310 μg/sec	(2080 μg/sec)

Corresponding Basin Water Concentrations:
Sodium: 9720 mg/1. Magnesium: 1055 mg/1

Salt Mass Emission Fraction:	0.00084%	(0.001%)

TABLE 4-14
EFFECT OF COOLING TOWER ON AMBIENT SALT CONCENTRATION (10)

A. Summary Statistics for Down Wind Minus Background Concentration for Cooling Tower

Sta	No Cases	Mean mgr/m^3	Std Dev ugr/m^3	Max Value ugr/m^3	Min Value ugr/m^3	Confidence That Increase is Less Than Std Dev (%)
3	21	-0.3101E 01	0.3590E 01	0.4552E 01	-0.1115E 02	97
4	53	0.4648E 01	0.5593E 01	0.3181E 02	-0.1520E 01	57
5	54	-0.3211E 01	0.4238E 01	0.1637E 02	-0.6419E 01	84
6	59	-0.2417E 01	0.3095E 01	0.5779E 01	-0.7797E 01	96
7	51	0.2553E 01	0.3611E 01	0.1170E 02	-0.6590E 01	61
8	63	-0.1978E 01	0.3975E 01	0.1022E 02	-0.8790E 01	93
9	50	-0.1236E 01	0.3349E 01	0.1024E 02	-0.7463E 01	92
10	3	-0.4548E 01	0.1170E 01	-0.2900E 01	-0.5504E 01	--
11	44	0.7658E 00	0.4698E 01	0.1560E 02	-0.6409E 01	85

B. Summary Statistics for Down Wind Minus Background Concentration for Spray Modules

Sta	No Cases	Mean mgr/m^3	Std Dev ugr/m^3	Max Value ugr/m^3	Min Value ugr/m^3	Confidence That Increase is Less Than Std Dev (%)
3	21	-0.1451E 00	0.7726E 01	0.1799E 02	-0.8405E 01	84
4	41	0.1186E 02	0.1997E 02	0.1036E 03	-0.7852E 01	66
5	43	0.7576E 00	0.6408E 01	0.3179E 02	-0.5484E 01	81
6	43	-0.2935E 01	0.3166E 01	0.7399E 01	-0.1138E 02	97
7	[illegible]7	0.3349E 01	0.2953E 01	0.1342E 02	-0.1011E 01	(44)
8	54	-0.2797E 01	0.4178E 01	0.1336E 02	-0.1173E 02	95
9	40	-0.1072E 01	0.2370E 01	0.8539E 01	-0.4251E 01	93
10	6	-0.5033E 01	0.1245E 01	-0.3003E 01	-0.6554E 01	--
11	40	0.3483E 01	0.9393E 01	0.4857E 02	-0.6938E 01	73

TABLE 4-15

VEGETATION ACUTELY AFFECTED BY SALT SPRAY* (38)

Beach plum
Bermuda grass
Black gum
Blackjack oak
Camphor weed
Cinnamon fern
Cyperus
False heather
Flowering dogwood
Golden rain tree
Horseweed
Marsh fern
Marsh St. John's wort
Red maple
Rose
Rose mallow
Royal fern
Sassafras
Scrub oak
Smilax
Spannish oak
Stagger-bush
Sumac
Trumpet creeper
Virginia creeper
Wild bean
Wild black cherry

---

*Plants showing acute foliar injury after 3 to 15 seawater spray treatments.

TABLE 4-16

PLANTS ACUTELY AFFECTED BY SALINITY (1)

Sensitive to Salt Spray*

Beach plum
Bermuda grass
Black gum
Blackjack oak
Camphor weed
Cinnamon fern
Cyperus
False heather
Flowering dogwood
Golden rain tree
Horseweed
Marsh fern
Marsh St. John's wort
Rose
Rose mallow
Royal fern
Sassafras
Scrub oak
Smilax
Spanish oak
Staggerbush
Sumac
Trumpet creeper
Virginia creeper
Wild bean
Wild black cherry

Sensitive to Saline Soil+

Alfalfa
Algerian ivy
Arborvitae
Beans
Bell pepper
Bottle brush
Boxwood
Broadbean
Burford holly
Cabbage
Carrots
Clovers
Corn
Dodonea
Flax
Heavenly bamboo
Hibiscus
Juniper
Lantana
Lettuce
Meadow foxtail
Oleander
Onion
Orchardgrass
Pineapple guava
Pittosporum
Potato
Pyracantha
Rose
Silverberry
Star jasmine
Sweetpotato
Texas privit
Viburnum
Xylosma

---

*Plants showing acute foliar injury after 3-15 sea water spray treatments.

+Plants showing more than a 10% relative yield reduction when growing in less than 4 m mhos/cm (ECe).

TABLE 4-17

RESPONSE OF VARIOUS ORNAMENTAL PLANTS TO SEAWATER SPRAY[*] (15)

Resistant[+]

Pachysandra terminalis
Ilex opaca
Ilex glabra
Aesculus parviflora
Enkianthus campanulatus
Prunus laurocerasus
Cotoneaster salisifolia
Ligustrum vulgare nanum
Ligustrum obtusifolium regelianum
Myrica pensylvanica
Abelia x grandiflora
Taxus bacatta repandens
Taxus media 'Hicksi'
Larix decidua
Osmanthus ilicifolia
Buxus sempervirens
Hedera helix
Euonymus alatus
Viburnum rhytidophyllum
Cedrus atlantica glauca
Pinus strobus
Pinus sylvestris
Pinus thunbergi
Pinus nigra
Juniperus horizontalis plumosa
Juniperus chinensis pfitzeriana
Elaeagnus angustifolia
Morus alba

Sensitive[‡]

Franklinia alatamaha
Clethra alnifolia
Stewartia ovata grandiflora
Cotoneaster horizontalis
Pyracantha coccinia
Forsythia x intermedia
Magnolia virginiana
Ilex verticallata
Crataegus phaenopyrum
Albizia julibrissin rosea
Ailanthus altissima
Vaccinium pensylvanica angustifolium
Cornus mas
Cornus kousa
Syringa vulgaris
Rhus aromatica
Acer palmatum atropurpureum
Betula pendula
Ginko biloba
Sorbus aucuparia
Gleditsia triacanthos
Cercis canadensis

Very Sensitive[§]

Cornus florida
Cotoneaster adpressa praecox
Rhus glabra
Platanus acerfolia pyramidalis
Vaccinium corymbosum
Campsis radicans
Koelreuteria paniculata
Malus sp.

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[*] Plants growing at Horticulture Farm 1, Rutgers University, sprayed with undiluted seawater on three consecutive days.

[+] No damage.

[‡] 20 to 40% of the leaf injured.

[§] Over 40% of the leaf injured.

TABLE 4-18

ENVIRONMENTAL CONDITIONS PRODUCING VISIBLE SALT INJURY TO NATIVE VEGETATION NEAR FORKED RIVER, N.J. (15)

Distance From Shore (meters)	Ambient Airborne Salt Concentration (ug/m^3)	Meteorological Conditions	Deciduous Vegetation Damage
50	382	Persistent onshore winds-15 mph without rain for several days	Leaf scorch & twig dieback up to 375 m from shore
650	62	Same	No visible damage

Note: The symbol "ug" represents micrograms.

TABLE 4-19

SUMMARY OF SODIUM AND CHLORIDE SEASONAL MEANS AND RANGES FOR ALL SPECIES AND SITES. DATA ARE EXPRESSED AS u_g/g ON A DRY-WEIGHT BASIS SAMPLING PERIOD EXTENDED FROM MAY 1974 TO APRIL 1975 (37)

Species and Site	Na^+ Load		Cl^- Load	
	Mean	Range	Mean	Range
Virginia pine, site 1, PV-1	51.1	24.1-98.8	346.8	291.7-434.3
Virginia pine, site 2, PV-2	73.7	43.5-121.6	405.3	299.1-506.2
Virginia pine, site 3, PV-3	101.6	47.2-176.8	409.7	326.7-544.2
Virginia pine, site 4, PV-4	73.6	33.1-119.8	431.0	270.5-718.6
Virginia pine, site 5, PV-5	70.7	38.9-97.9	393.7	278.6-497.7
Virginia pine, site 6, PV-6	464.3	293.4-631.2	1397.7	506.2-2765.0
Black locust, site 1, RP-1	99.5	44.8-216.1	594.3	298.9-1218.1
Black locust, site 2, RP-2	98.0	45.0-197.9	434.1	275.7-813.3
Black locust, site 3, RP-3	127.3	44.7-291.0	1269.4	565.5-2606.7
Sassafras, site 1, SA-1	86.6	34.5-194.6	157.6	106.8-181.8
Sassafras, site 2, SA-2	87.6	43.1-161.5	183.7	142.3-245.0
Sassafras, site 3, SA-3	77.0	36.9-154.9	290.9	151.7-614.6
Dogwood, site 1, CF-1	54.4	41.8-70.4	2046.3	570.8-3817.2

TABLE 4-20

SUMMARY OF SODIUM AND CHLORIDE CONCENTRATIONS ON A DRY-WEIGHT BASIS IN CERTAIN PLANTS (22)

	Na^+, ppm		Cl^-, ppm	
	Normal*	Toxic+	Normal*	Toxic+
Tops				
Corn	127			
Buckwheat	368			
Sunflower	392			
Oats	460			
Sweet clover	483			
Tobacco	575			
Pea	665			
Saltwort	1,790			
Broad bean	1,910			
White mustard	3,220			
Saltbush	11,400			
Leaves				
Peach	5,000			
Snap bean	200	400 to 7,000		
Grape	200 to 600			
Tomato	5,000			
Apple				2,100
China aster			46,000	78,000
Azalea			3,000 to 5,000	14,000 to 30,000
Snap bean				40,000
Cherry			3,000 to 4,000	
Sweet corn			3,000 to 5,000	
Grape				15,000
Lettuce			50,000	
Peach				10,000 to 15,000
Poinsettia				47,000
Potato			20,000	

*Intermediate concentration; not low, high, or toxic.

+Growth reduction or toxicity symptoms.

TABLE 4-21

EXTENT OF INJURY TO PLANTS EXPOSED TO SEAWATER MIST FOR VARIOUS LENGTHS OF TIME (15)

Species	Hours Under Mist	Extent of Injury
Robinia pseudo-acacia	0	No injury
	2	Slight tip and margin necrosis
	4	Moderate tip and margin necrosis
	6	Extensive necrosis
	8	Partial defoliation
	10	Complete defoliation
	12	Complete defoliation
Pinus thunbergi	0	No injury
	24	No injury
Pinus strobus	0	No injury
	24	No injury
Geranium sp.	0	No injury
	24	Complete defoliation
Contender snap bean	0	No injury
	24	Extensive necrosis

TABLE 4-22

EFFECTS OF SALT-SPRAY APPLICATIONS ON THE NUTRIENT CONTENTS AND METABOLIC INDEX IN SOYBEAN LEAVES* (19)

Salt (NaCl) treatments,+ kg ha^{-1} week^{-1}	Elements,‡ %						Metabolic Index§ (1)
	Ca	Mg	K	P	Cl	Na	
0	1.30	0.50	1.90	0.33	0.069	0.065	32.10
1.82	1.05	0.37	1.70	0.26	0.260	0.078	9.88
3.64	1.49	0.56	2.10	0.36	0.503	0.114	7.23
7.28	1.35	0.53	2.00	0.34	0.689	0.142	5.08
14.56	1.60	0.67	2.20	0.42	1.310	0.211	3.21
Mean	1.36	0.58	2.00	0.34	0.567	0.122	11.6
Least significant difference (0.05)	N.S.	0.18	N.S.	N.S.	0.114	0.091	9.54
Coefficient of variation, %	19.4	22.5	19.1	20.4	13.0	48.8	53.4

---

*Sampled from entire plant canopy after last treatment.

+Applied as concentrated sodium chloride solution spray on a weekly basis for 8 weeks. To convert to pounds per acre, divide by 1.1.

‡Average of four replications, expressed as percentage dry weight. To convert to parts per million, multiply by 10^4.

§Determined by dividing (Ca + Mg + K + P) by (Cl + Na).

#N.S. indicates insignificant difference between values.

TABLE 4-23

EFFECTS OF SALT-SPRAY APPLICATIONS ON THE NUTRIENT CONTENTS AND METABOLIC INDEX IN CORN LEAVES* (19)

Salt (NaCl) treatment,+ kg ha^{-1}, $week^{-1}$	Elements,‡ %						Metabolic Index§ (1)
	Ca	Mg	K	P	Cl	Na	
0	0.43	0.28	3.18	0.32	0.312	0.061	11.7
1.82	0.44	0.29	3.20	0.34	0.364	0.095	9.3
3.64	0.36	0.24	2.83	0.30	0.471	0.110	6.0
7.28	0.30	0.18	1.90	0.22	0.804	0.211	2.6
14.56	0.36	0.22	2.23	0.29	1.030	0.313	2.2
Mean	0.38	0.24	2.66	0.29	0.596	0.158	6.5
Least significant difference (0.05)	0.10	N.S.	0.89	N.S.	0.094	0.117	2.4
Coefficient of variation, %	16.7	21.6	21.7	21.1	10.2	48.4	23.8

---

*Sampled from point of ear attachment after last spray treatment.

+Applied as concentrated sodium chloride solution spray on a weekly basis for 8 weeks. To convert to pounds per acre, divide by 1.1.

‡Average of four replications, expressed as percentage of dry weight. To convert to parts per million, multiply by 10^4.

§Determined by dividing (Ca + Mg + K + P) by (Cl + Na).

#N.S. indicates insignificant difference between values.

TABLE 4-24

MEANS* OF NUTRIENT CONTENTS AND METABOLIC INDEX FOR SOYBEANS AND CORN FROM THE CHALK POINT COOLING TOWER MONITORING PROGRAM - 1973+ (19)

Radius,‡ km	Elements, § % Ca	Mg	K	P	Na	Cl	Metabolic Index (1)
				Soybeans			
1.6	1.22	0.67	2.17	0.28	0.074	0.073	29.9
4.8	1.56	0.55	1.90	0.28	0.081	0.100	23.5
9.6	1.53	0.57	2.00	0.29	0.085	0.081	26.9
Mean	1.44	0.60	1.99	0.28	0.080	0.085	26.8
Least significant difference (0.05)	N.S.#	0.07	N.S.	N.S.	N.S.	N.S.	N.S.
Coefficient of variation, %	19.3	7.2	16.9	12.7	7.5	17.1	11.1
				Corn			
1.6	0.45	0.34	2.40	0.28	0.072	0.180	14.1
4.8	0.48	0.27	2.30	0.28	0.071	0.224	11.2
9.6	0.48	0.30	2.20	0.27	0.077	0.198	11.8
Mean	0.47	0.30	2.26	0.28	0.074	0.200	12.4
Least significant difference (0.05)	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Coefficient of variation, %	17.5	13.6	10.5	10.9	13.2	14.9	11.6

---

*Each data entry represents the mean of three replications at four sites within each radius (Figures 3 and 4).

+The data for 1973 represent the baseline information for the Chalk Point Cooling Tower Monitoring Program.

‡The 1.6, 4.8, and 9.6 km equal 1, 3, and 6 miles, respectively.

§Tissue contents represented on a dry weight basis from samples taken at point of ear attachment for corn and the entire canopy of soybean leaves at the time of flowering.

#N.S. indicates insignificant difference between values.

TABLE 4-25

RESPONSE OF NINE DECIDUOUS WOODY SPECIES OF PLANTS TO SALINE AEROSOLS (24)*

	Total dose (micrograms Cl^-/cm^2)										
	2.4	4.8	12	24	48	72	96	120	144	192	264
Witch-hazel				0					0	0	1
				6					5	4	3
Golden rain tree				0					0	3	5
				2					1	0	0
Red maple					0	1	3	4	7	8	11
					8	6	3	0	0	0	0
Silk tree				0	0		1	2	3	4	6
				3	2		0	0	0	0	0
Black locust				0	0		1		3	4	
				2	1		0		0	0	
Chestnut oak					1		6	15	18		19
					9		1	0	0		0
Forsythia					5		10		12	13	
					5		0		0	0	
Flowering dogwood	1	3	13	33	42		43		44	46	48
	24	17	11	5	1		0		0	0	0
White ash	4	6	15	17	18		19		21	22	23
	21	13	7	0	0		0		0	0	0

---

* Exposure period = 4 hours, 95% aerosol salt particles between 50 and 150 microns in diameter, relative humidity = 85% during and after exposure.

Note: For each species: the upper number is equal to the number of plants injured by a dose less than or equal to the value given; the lower number is equal to the number of plants uninjured by a dose greater than or equal to the value given.

TABLE 4-26

RESPONSE OF TWO CONIFEROUS SPECIES TO SALINE AEROSOLS (24)*

	Total dose (ug Cl cm^{-2})								
Species of Conifer	7.2	14.4	36	72	120	180	216	288	576
Eastern white pine			0 65	22 55	43 30	62 1	72 0	92 0	102 0
Canadian hemlock	12 0	36 0	40 0	48 0	48 0	60 0	68 0		

---

*Plants given single 6 hour exposure at 85% RH to saline particles.

Note: For each species: the upper number is equal to the number of plants injured by a dose less than or equal to the value given; the lower number is equal to the number of plants uninjured by a dose greater than or equal to the value given.

TABLE 4-27

RESPONSE OF TWO DECIDUOUS WOODY SPECIES EXPOSED AT 85% RELATIVE HUMIDITY TO A SALINE AEROSOL* (24)

Species of Plant	Duration of Exposure (hours)					
	14	16	17	18	20.2	25.4
White flowering dogwood	0 15	4 11	4 5	9 0	14 0	15 0
White ash	0 4	10 0	15 0	20 0	25 0	26 0

---

* A mass mean diameter of 1.5 microns at a concentration of 1500-1700 micrograms Cl m^{-3}. For each species: the upper number indicates the number of plants injured by an exposure less than or equal to the value given; the lower number indicates the number of plants without injury after an exposure greater than or equal to the value given.

TABLE 4-28

SHOWS PERCENT OF INJURED BUSH BEAN WITH RELATION TO TRIFOLIATE SODIUM AND CHLORIDE ACCUMULATION IN PPM (27)

Plant	Salt Concentration $\mu g/m^3$	Percent Trifoliate Injury	Sodium	Chloride
One week	5	0	84.0	1148.0
	25	0.3	112.0	957.0
	75	18.7*	889.0	8630.0
Three weeks	5	0.7	204.0	2014.0
	25	1.7	496.0	6717.0
	75	17.6*	5820.0	32886.0
Five weeks	5	3.6	102.0	2789.0
	25	5.9	914.0	6254.0
	75	24.0*	12143.0	40700.0

* The injury column value within a particular weekly group is significantly different at 1% level of probability. Post-exposure conditions varied for the three ages of plants do not directly compare the three ages of plants past the termination of exposure.

TABLE 4-29

CASE STUDIES COMPARISON OF ENVIRONMENTAL DRIFT EFFECTS FOR POWER GENERATING PLANTS

Plant	Status	Drift Data	References
Hanford No. 2 NPP, Washington	Proposed (Freshwater)	During operation of the plant, cooling tower will cause slight increases in dispersion of small quantities of chemicals in drift; chemical deposition is less than the acceptable levels in irrigation practices.	53
Turkey Point, Florida	Pre-operational (salt water)	DMS; average difference between measured concentration with cooling tower operating and expected background concentration was 2 x 10^{-3} ug/m^2 ± 4.8 (s); highest monthly salt aerosol level for the mechanical draft towerwas 5 ug/m^3; operation of cooling tower did not increase background salt concentration by a measurable amount at any sampling station; no effects attributable to salt aerosol emissions from test cooling devices detected on indigenous plants and soil.	10, 27
Forked River, New Jersey	Proposed (Brackish)	DMS; short term exposures (several hours) to about 100 ug/m^3 produce foliar injury, while those with 60 ug/m^3 would not; long-term mean of 10 ug/m^3 aerosol salt might influence distribution and abundance of plants.	14, 15
Indian Point, New York	Pre-operational (Brackish)	DMS; aerosol salt background levels (11 months) $X = 1$ ug/m^3, range 0-6.15 ug/m^3. On-site maximum deposition = 79 kg/ha or 71 lb/acre; maximum short-term exposure that will not produce adverse effects on most susceptible species of plants under condition most conducive to injury is exposure = total deposition of 2 ug Cl/cm^2 in 6 hours; 85% RH and absence of precipitation during and after simulated saline mist.	24, 52

Note: The symbol "ug" represents micrograms.

TABLE 4-29 (cont'd)

Plant	Status	Drift Data	References
Chalk Point, Maryland	Pre-operational (Brackish)	DMS; partial operation of cooling towers from May-October, 1975, had no discernible effect on local vegetation or on tobacco, corn and soybeans.	21, 16, 17 20, 23
Jack Watson, Alabama	Postoperational (Brackish)	No data.	18
Southern California Edison, California	Postoperational, since 1970 (Freshwater)	No observed effects.	18
B. L. England, New Jersey	Postoperational (Brackish)	DMS; long-term average and deposition levels higher when plant operating than when not; drop deposited 1000 feet downwind; levels: 2-8 ug/m^3 (natural background), 8-28 ug/m^3 (induced).	18
Chevron Oil Co.	Postoperational, since 1957 (Saltwater)	Drift effects observed 100-150 m from cooling tower; trees 300 m west of cooling tower were ok.	18
P. H. Robinson, Texas	Postoperational (Brackish)	DMS; mathematical model of deposition predicted 15 lbs/acre-month, 1500 feet from cooling tower.	18
Exxon, New Jersey	Postoperational, Since 1968	Drift caused metal corrosion 150-200 m downwind; no visible effects on vegetation.	18

Note: The symbol "ug" represents micrograms.

TABLE 4-29 (cont'd)

Plant	Status	Drift Data	References
Fleetwood, England	Postoperational (17 years) (Saltwater)	No detrimental effects observed; trees and shrubs 500 m downwind healthy.	18
Three Mile Island Nuclear Station, Pennsylvania	Postoperational (Freshwater)	No measurable effects on vegetation from cooling tower drift deposition on natural vegetation observed; no effects onbird population.	29
Cayuga Lake, New York	Pre-operational (Freshwater)	No environmental impact expected; maximum on-site deposition estimated at 260 Kg/ha-yr, within 0.4 Km of the cooling towers.	73

---

1. DMS = Drift monitoring studies being conducted on pre- and post-operational level.

TABLE 4-30

FAUNAL SALT TOLERANCES

Species	Level Which Produces Some Observable Effect Dose	Nature of Response	References
Ringneck pheasant Cottontail rabbit	3 grams	Mortality	63
Bobwhite quail	1% NaCl solution	Weight loss	64
Chicks	7000 ppm	Decreased growth; 14-47% Mortality	65
Chicks	10000-12000 ppm	75-100% Mortality	65
Turkey poultry	4000 ppm	Increased Mortality	65
Ducklings	10000 ppm	43% Mortality	65
Chicks	5000-9000 ppm NaCl in Solution	Distress	66
Baby Chicks	5-10% NaCl in solution	Heavy mortality within one week	67
Adult pigs	5% NaCl ingested with feed but water supply restricted	Salt poisoning	68
Bufo viridis	75% seawater (2.34% NaCl solution)	Tolerates	69
Bufo melanostictus (8½ day old tadpoles)	.75% solution	Unaffected	70
Savannah sparrows	.55 molar NaCl-fed 10 days	No loss in body weight	71
White-footed mouse	.3 M NaCl for 10 days	Tolerates drinking water	72
Red-backed mole	.1 M NaCl solution	Tolerates	72

TABLE 4-31

BIRD IMPACTIONS RECORDED AT THREE MILE ISLAND NUCLEAR STATION COOLING TOWERS BY MONTH AND TOWER, JULY 27, 1973 THROUGH MAY 31, 1975 (29)

	Days Monitored	Tower 1	Tower 2	Tower 3	Tower 4	Total
Preoperation						
July 27-31, 1973	3	0	0	0	0	0
August	10	0	0	0	0	0
September	11	0	0	2	8	10
October	31	5	0	9	5	19
November	30	0	0	0	2	2
December	20	0	0	0	0	0
January, 1974	8	0	0	0	0	0
February	7	0	0	1	0	1
March	31	0	0	1	0	1
April	30	1	1	1	0	3
May	31	0	0	0	1	1
June 1-4	4	0	0	0	0	0
Subtotal Preoperation	216	6	1	14	16	37
Operation						
June 5-30, 1974	26	0	0	0	0	0
September	30	0	0	0	0	0
October	31	2	5	6	13	26
November	30	0	0	1	0	1
March, 1975	31	0	0	0	0	0
April	29	0	0	1	1	2
May	31	0	0	0	0	0
Subtotal Operation	208	2	5	8	14	29
Total	424	8	6	22	30	66

SECTION 5

WEATHER MODIFICATION

5.1 INTRODUCTION

Weather modification is becoming an important topic in environmental assessment of the effects of evaporative cooling towers. One of the most easily observed cooling tower-related phenomena is fogging-icing and the most common inquiry at environmental hearings concerns its frequency and intensity.

Other weather conditions long suspected to be caused by cooling towers include cloud enhancement and precipitation. Because of the naturally occurring cyclic nature of climate, enhancement of precipitation and of clouds resulting from cooling tower (CT) operation is not easily analyzed. Cloud enhancement as reported in much of the literature, seems insignificant.

The processes involved in producing weather modification directly from wet cooling towers requires an understanding of cloud physics, including evaporation-condensation, nucleation, and thermodynamics. Such topics will not be considered in great detail in this report, since only a general description is necessary to relate the impact of cooling towers on weather modification.

Numerical models which predict weather modification will be briefly reported because the models used to predict fogging-icing frequency, plume rise, and plume length are particularly numerous and have great disparity in results. Only in papers since 1974 has any serious comparison of numerical models been made with observed phenomena. This comparison has been restricted to plume rise, plume length and salt deposition. Although models exist for precipitation and cloud enhancement, their predictions have not been sufficiently verified by observed data.

5.2 FOGGING-ICING FREQUENCY AND DURATION

An evaluation of the fogging-icing frequency includes: induced fogging which results from the contribution of water vapor at distances beyond the visible plume and fogging which results from actual visible plume intersection with the ground. With regard to a direct visible plume and ground intersection, the downwash in the wake of a cooling tower is a function of tower design and height. Better aerodynamic cooling tower design and enhanced plume buoyancy will decrease the fogging-icing frequency and duration.

Tower design can be categorized into four basic types: mechanical draft, natural draft, wet/dry and fan-assisted natural draft. Field studies of the fan-assisted or wet/dry towers have not been made, so that these will not be considered.

Since there does not appear to be any measurable downwind contribution of water vapor from cooling towers, it is difficult to attribute induced downwind fogging directly to cooling towers (W. Dunn, personal communication). Kramer et al. (1) studied the environmental problems of natural draft cooling towers (NDCT) at the Amos Plant in West Virginia and found no evidence of induced fogging.

The question of fogging resulting from a visible plume intersecting the ground remains unclear. For natural draft cooling towers (NDCT), the consensus is that no fogging will occur unless there is a sharp rise in elevation and conducive meteorological conditions exist. Several studies support this contention (1,2,3). Slawson et al. (2) did not note ground fog from NDCT's in a five-year period of observation at the Paradise Steam Plant, and Moore (3) at the CEGB did not report any ground fog from NDCT's in England.

Spurr (4) in a study of the region surrounding Ratcliffe found no meaningful statistical increase of fogging incidence (Table 5-1). In fact, a decrease was noticeable over a period of years (Figure 5-1). Lack of ground fog with NDCT's was attributed to tower design because the tower was simply too high to allow the visible plume to intersect the ground even with downwash effects under high wind conditions, stable lapse rates of temperature, and high humidity. In extreme cases, downwash appeared to reduce plume height to 50% of the tower height. However, buoyant effects soon raised the cooling tower plume to its equilibrium height within several kilometers.

Lack of ground fog cannot be used to characterize mechanical draft cooling towers (MDCT). Hanna (5) noted that downwash occurred 50% of the time with the MDCT's while NDCT's had fewer problems with downwash. However, plumes that do touch the ground will rise again within 250 m because of their buoyancy (5).

In an environmental report for Indian Point, a round MDCT design was recommended because of superior aerodynamic characteristics (6). However, only wind tunnel studies have been used to evaluate the round tower design so that field characteristics have not been completely determined (7). Downwash is greatly enhanced by the rectangular MDCT design, and since the MDCT height is not sufficient to counteract downwash, fog near the tower is expected to be adversely frequent with winds greater than 2 m/sec, high relative humidity (approximately 95%) and stable temperature lapse rates. Exit velocity, buoyant effects of plume and tower heights were not sufficient to counteract downwash from the rectangular MDCT's. However, despite the problems introduced by the aerodynamically poor design of rectangular towers, fogging effects are limited usually to the plant property due to the plume's buoyancy.

Factors influencing icing frequency and duration are similar to those causing fogging. The difference is that during cold weather, the frequency and duration of cooling tower plumes are enhanced because the much lower ambient temperature leads to condensation of more cooling tower water vapor. The quantitative plume frequency and duration comparison at different temperatures, relative humidities and temperature lapse rate classes have not been established in field studies. Such studies have been limited to numerical model predictions. Of course, the ambient temperature must be below freezing to have icing. Hence, the frequency of temperature below freezing is necessary to establish the seriousness of icing. Long freezing periods will prevent accumulated ice from disappearing.

Fogging is dependent upon the tower type, and this is true for icing as well. At Chalk Point, the NDCT does not cause more than a few millimeters of ice on structures and wires located on the plant site (8). From field observations, Slawson et al (2) determined that icing from the NDCT's at Paradise is not significant.

As in the case of fogging, icing is more of a problem from MDCT's than from NDCT's. An extreme case occurred at Palisades (Consumer Power Co.) on Lake Michigan during December, 1976 (9). Extremely heavy icing coated trees and the ground on the lee wind side of the five rectangular MDCT's. A conservative (worst case) estimate indicated that five to six inches of ice coated the trees, and 12 inches lay on the ground. Glaze ice of ¼-inch thickness extended as far as 240 m down wind. The cause of this phenomenon was not documented. Whether there was failure of the eliminators, different operating conditions, or severe weather was not discussed. Because of the unusually cold winter of 1976-77, it is plausible that severe weather seriously aggravated this icing condition.

Although other reported cases of icing have not been severe, MDCT's do seem to cause more of an icing problem than NDCT's due to the same reasons as in the case of increased fogging and because of the larger droplets being entrained by the forced draft.

The net icing effect at off-plant locations from MDCT's are not necessarily worse than for NDCT's. This is because larger droplets leaving the tower are confined to an area within the plant boundaries, since they have a larger fall velocity. Actual type comparisons have not been performed in the literature with regard to field studies of icing; only individual towers have been evaluated from field studies and from numerical model predictions.

5.3 METEOROLOGICAL CONDITIONS CONDUCIVE TO FOGGING AND ICING

Ambient meteorological conditions for MDCT (mechanical draft cooling tower) fogging include: wind speeds greater than 2 m/sec, stable temperature lapse rates, relative humidity greater than 95% and low dry bulb temperatures (usually less than 50°F). These conditions cause downwash, low dispersion rates, low evaporation rates and additional condensation, respectively. With regard to fogging frequency, these parameters have never been correlated quantitatively with fogging frequency or duration, except with numerical model predictions in environmental reports. Icing requires freezing temperatures; hence, the number of days below freezing is a determining factor of the icing potential.

Site-specific climatology is a prerequisite to establishing regions where fogging-icing may present particular difficulties. The problem then becomes one of finding a model accurate enough to establish fogging frequency and duration. To date, only one study has been prepared to categorize general regions where the fogging frequency may present potential problems. However, the model has no verification with field data. The danger of making regional fogging potential classifications on scales larger than 10 km is that mesoscale phenomena, caused by conditions such as mountain-valley flow and sea-breeze regimes, reduce the accuracy of general classifications. Fogging potential classifications can be more accurately represented by types of climatology rather than by region. However, to date no such classifications study has been conducted.

Generally, the major quantitative drawback to the determination of fogging-icing frequency has been the lack of field studies. Only recently have models been independently evaluated and the final results are not yet available (10,11). As complete as this evaluation will be, the field data base contains only about 39 observations. As a result, only generalizations can be drawn from present site studies; specifics apply only to a single site. In addition, nearly all of the field studies were performed at natural draft cooling towers (NDCT) rather than at MDCT's. Thus, there is a considerable lack of data on MDCT behavior (12), resulting in a speculative assessment of atmospheric conditions influenced by MDCT plumes.

5.4 ADVERSE EFFECTS OF FOGGING AND ICING

Fogging-icing effects appear to locally dissipate. Only in rare instances can the effect at distances of five or more kilometers from cooling towers be noticed (13). In one instance, a snow crystal cloud extended to 43 km downwind of the cooling tower and the plume was elevated. But, under extremely cold ambient conditions and in situations where the ground elevation rises, such a plume may reach ground levels. Although model results vary from observed values by factors of two or three (11), most concur within one order of magnitude. On the basis of model predictions, it is not reasonable to expect fogging and icing beyond 10 km unless topography within the area rises substantially. In this case, plume intersection with the ground at large distances is possible under certain meteorological conditions. Under these circumstances, some damage to vegetation as a result of icing and obstruction of sight due to fogging could occur. For example, a cooling tower located in a valley might present such a problem. Nearby airfields might be adversely affected with visual obstruction due to particularly long cooling tower plumes. However, the visual obstruction is of short duration (8) and is of little concern unless the plume happens to be covering certain critical places, such as the runway.

On the basis of wind tunnel and field studies, MDCT's pose a more serious fogging and icing threat than NDCT's (5,9,14,15). The Palisades incident (9) severely damaged vegetation within about 91 meters, but this incident was abnormal. Damage to vegetation in the area between about 90 m and 240 m where ice glaze accumulated from 0.25 to 2.0 inches showed moderate to minimal damage. No description beyond 240 m is mentioned. NDCT's appear to not cause much of a problem in this regard.

5.5 CLOUD ENHANCEMENT

Although an increase of clouds downwind of a cooling tower has been noted qualitatively many times (1), the overall quantitative enhancement has not been established through field studies. Two types of cloud enhancements are considered in the literature: the condensed cooling tower phase and cloud physics processes. The former is evaluated by observation of plume lengths (Tables 5-2 and 5-3). Some of these observations are available through the Argonne National Laboratory validation progress report (11); these observations collected from other sources probably contain the best information in the literature. Another group involving cloud physics processes is not well-documented, since the cooling tower contribution by this mechanism is subtle. The cooling tower plume may actually disappear, but because of additional heat and moisture added to ambient air, it may cause a cloud to form at some point downwind. This type of cloud would typically occur in a convective process which forms cumulus type clouds. During a stable process, the cooling tower plume and stratus clouds usually merge so that one is indistinguishable from the other.

The enhancement resulting from cloud physics processes has been estimated by radiosonde data collected at Nashville, Tennessee (5) and a numerical one-dimensional cloud physics model (16). There are numerous other one-dimensional cloud physics models which are basically the same, however, the Kramer et al.(16) model has been more frequently evaluated (5).

Hanna (5) has determined that for the single cell 1000 MW station (typical NDCT now in use) cloud frequency occurrences are 39%. Of course, predicted cloud occurrences are spread over all directions so that the impact on any one sector should be less than 39%.

For the two cloud enhancement types, quantitative measurement of cloud enhancement has not been verified by field observations. Generally, environmental reports contend that some enhancement is expected but the effect on any one sector is not significant, probably less than 10%. Perhaps, these impact statements are supported by unverified numerical models or are referenced by qualitative reports concerning the non-importance of induced cooling tower clouds. Usually, none is supported by complete field studies. There is often no delineation between estimated enhancements of natural draft cooling towers and those of mechanical draft cooling towers. If a numerical model is used, then the difference is a result of various input parameters of natural draft cooling towers and mechanical draft cooling towers.

Regarding cloud physics models, Auer et al.(17) measured the Aitken Condensation Nuclei (ACN) concentration from four coal-fired power plants. The mid-size power plant of 1000 MWe produced ACN plumes 200% greater than background levels for one to two hours down wind. For example, the ACN count started at about 9000/cm^3, but then dropped to about 1000/cm^3 after two hours. The large plant produced ACN for about four hours down wind. In this case, the width of the ACN plume increased to 25 km and then remained constant at 7 to 10 km out to 50 km. Because such nuclei aid cloud formation, knowledge of their concentration may be useful in estimating probabilities of additional cloud formation.

In sum, cooling towers modify natural cloud formations (1,5). The extent of the modification has not been fully established by field observation (see Table 5-1). Present day cooling towers do not produce clouds when ambient conditions are not fertile.

5.6 METEOROLOGICAL CONDITIONS CONDUCIVE TO CLOUD ENHANCEMENT

The meteorological conditions which induce additional clouds are determined by the clouds already present. For a cloud to result from an extended cooling tower plume, the conditions include stable stratification, high relative humidity (RH), cool temperatures and minimal insolation. Typically, under these conditions the clouds formed will be of the stratus variety.

Cooling tower plumes are influenced by ambient RH conditions. For example, for 250 MW towers, all plumes are less than 300 m long with RH less than 75%; but for RH between 75% and 90%, 40% of the plumes are short, 40% medium and 20% are long (more than 900 m) (4). Brennan et al.(18) observed that temperature-humidity soundings in the vicinity of towers would serve as effective predictors of plume rise and persistence. However, no significant relationships between plume rise and wind speed, plant load or ambient temperature were observed. Other observations (2) indicated that downwash, which is a function of wind speed, reduced visible plume length and moisture content (Figure 5-2).

For induced cumulus clouds, conditions similar to a tropical regime with convective thermals exist, characteristically exhibiting high RH and warm temperatures in generally unstable conditions in which cumulus clouds form. The cloud dynamics and microphysics involved in cloud formation involve many parameters such as saturation vapor pressure, droplet concentration, droplet size, relative humidity, dry bulb temperature, absolute humidity, temperature lapse rate, latent heat release, vertical velocity and entrainment. The rate of cloud water production is dependent upon these parameters and is obtained from equations which are summarized very well by Hanna (5). Because of the complexity of the process, it is not possible to predict when a cloud will be formed unless the whole system of equations is used. Several numerical models have been created to perform this task, with the one of Kramer et al. (16) seeming to be reliable (5). In general, if conditions are fertile for natural cloud formation, then a cooling tower will accelerate and augment the formation.

5.7 ADVERSE EFFECTS OF CLOUD ENHANCEMENT

If it is assumed that cooling tower emissions do not significantly augment clouds over a specific area, then the adverse effects are small. Perhaps agricultural areas, such as the grape-growing regions of New York State, may be particularly sensitive to slightly reduced sunshine, but other areas would not suffer. However, no data supports this contention.

5.8 PRECIPITATION ENHANCEMENT FREQUENCY

Precipitation enhancement is documented in the literature, but measurement of the increased frequency for precipitation has not been obtained and documented. Kramer et al.(13) measured a maximum of 2.5 cm snowfall from natural draft cooling tower plumes from the Amos Power Plant when no other precipitation in the area existed. This occurred several times while they were obtaining plume data. At a power station with cooling towers in India, monsoon rain increased by about 25% at a station one kilometer away (19). Even with non-tropical environments and more environmentally clean stations, precipitation augmentation may exist. Hanna (5) suggested precipitation was enhanced, but offered no direct evidence.

Martin (20) did not find any statistically meaningful change in the rainfall around eight natural draft cooling towers at a 2000 MW station (Table 5-1). In testimony by Montz from the New York State Public Service Commission Staff (7), precipitation enhancement was not considered significant. Huff (21) projected less than 1% augmentation of stable rainfall resulting from a 2200 MW plant with two cooling towers rejecting 8.3×10^9 Btu/hr and 14,700 gpm of water vapor. Snow enhancement from the lake effect would be two to five inches at this Illinois plant which is about 5% of the annual snowfall. Convective showers might also be augmented.

During the winter of 1975-76, snowfall from the plumes of large natural draft cooling towers of power plants was observed 8 to 43 km away. Snow accumulations of up to 2.5 cm were found on the ground at about 30 km from the cooling towers, and visibility was restricted to less than 1600 m in the tower plume near ground level (13). AEP's Amos Plant with three natural draft cooling towers was used for this observation.

The knowledge of environmental effects caused by injections of large amounts of waste heat into the atmosphere from large power parks or complexes, such as those proposed in Louisiana, Florida and Pennsylvania with capacities as much as 10,000 MWe, is limited. A power center of 15 GWe rejecting heat over a ten-mile distance to the atmosphere would cause a 10°F temperature rise if once-through cooling were used, or about a 1°F drop if evaporatively cooled in a desert region; otherwise the only other predicted observable effect of cooling towers, wet or dry, would be about a 0.5% increase of cloudiness, again in a desert region. Once-through cooling of this intensity would cause a 3 or 4% cloudiness increase in a moist climate, but not in the desert (22).

Precipitation frequency enhancement by cooling towers is not easily documented because of the natural variability and cyclic nature of precipitation. A change in precipitation around the locality of a cooling tower may simply be a normal occurrence.

5.9 METEOROLOGICAL CONDITIONS CONDUCIVE TO PRECIPITATION ENHANCEMENT

In general, conditions which induce clouds will produce additional precipitation. Conditions for precipitation production must be fertile for the enhancement to occur. Differences between cloud and precipitation formation involves the additional process of coalescence, whereby a droplet becomes large enough to counteract upward vertical air velocities and evaporation below the clouds. In the snowfall at the Amos Plant, Kramer et al.(13) noted that the snowfall did not occur until the ambient temperature fell below 13.6°F. This seemed to be a necessary condition, but not a sufficient one.

High RH and stable conditions existed at the time of this snowfall.

Convective precipitation augmentation by cooling towers has not been observed, except by Selvan _et al._ (19). However, insufficient information exists to quantitatively determine precipitation enhancement, thereby rendering the selection of meteorological conditions beyond general descriptions useless for estimating enhancement.

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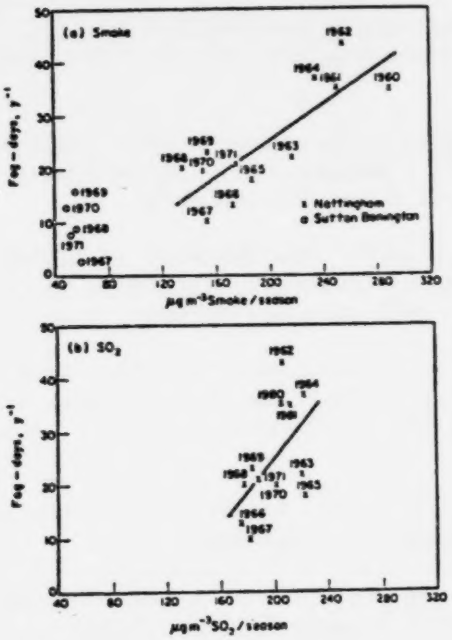

Figure 5-1 Incidence of fog and seasonal smoke and SO_2 (4)

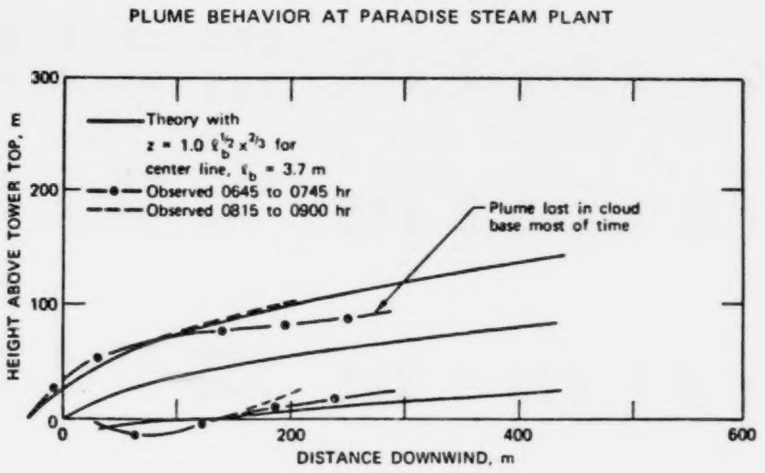

Figure 5-2 Predicted and observed cooling tower plume behavior, Sept. 7, 1972 (2)

TABLE 5-1

CONDITIONS BEFORE AND AFTER COMMISSIONING OF THE POWER STATION (4)

Site	Distance from Ratcliffe (km)	Mean 1960-1967	Mean 1968-1971	Change	Scatter and significance
(a) Rainfall, (mm/yr)					
Sutton Bonington	4	606	627	+21	e.g. Sutton Bonington increase
Nottingham	12	608	603	-5	95% confidence limits on means
Morley	15	724	702	-22	= ± 117 and ± 138 respectively
Derby	16	672	697	+25	
Watnall	16	733	724	-9	Students of increase
Newtown Linford	20	682	679	-3	= 0.22 for 10 degrees-of-freedom
Cranwell	56	586	618	+32	Value of 2.23 required for 5%
Wittering	61	582	631	+49	significance-increase
Terrington	106	584	562	-22	not significant
Skegness	112	630	589	-41	
(b) Bright sunshine (h/day)					
Sutton Bonington	4	3.61	3.54	-0.06	
Nottingham	12	3.29	3.49	+0.20	
Morley	15	3.56	3.55	-0.01	e.g. Newtown Linford decrease
Derby	16	3.59	3.48	-0.11	95% confidence limits
Watnall	16	3.38	3.27	-0.11	± 0.24 and ± 0.28 respectively
Newtown Linford	20	3.62	3.37	-0.25	t = 1.63 for 10 degrees-of-freedom
Cranwell	56	3.99	3.93	-0.06	decrease not significant
Wittering	61	4.10	3.91	-0.19	
Terrington	106	4.05	3.87	-0.18	
Skegness	112	4.09	4.11	+0.02	

TABLE 5-1 (cont'd)

Site	Distance from Ratcliffe (km)	Mean 1960-1967	Mean 1968-1971	Change	Scatter and significance
(c) Fog, at 0900 h (days/yr)					
Sutton Bonington	4	19	12	-7	e.g. Wittering increase
Nottingham	12	27	21	-6	95% confidence limits
Morley	15	--*	--	--	± 6 and ± 2 respectively
Derby	16	32	16	-16	t = 1.63 for 10 degrees-of-freedom
Watnall	16	41	33	-8	increase not significant
Newtown Linford	20	22	18	-4	e.g. Derby decrease
Cranwell	56	25	23	-2	95% confidence limits
Wittering	61	23	28	+5	± 12 and ± 2 respectively
Terrington	106	20	18	-2	t = 2.55 for 10 degrees-of-freedom
Skegness	112	21	12	-9	decrease significant

*Not recorded.

TABLE 5-2

COMPARISON OF OBSERVED AND PREDICTED PLUME LENGTHS (2)

Date	Time	Observed length, m	Cooling towers operating	K	Predicted length (X_E), m
2/10/71	0653 to 0750	532 to 866	1	1.5	407
3/2/71	1010 to 1050	106 to 167	2	1.0	156
3/4/71	0640 to 0720	300 to 465	1	1.5	400
9/7/72	0815 to 0942	200	3	1.0	196
9/7/72	0945 to 1045	150	3	1.0	158

TABLE 5-3

SOURCE AND AMBIENT DATA (2)

Date	Time	w_0, m/sec	$T_{p_0 v}$, °K	T_a, °K	q_{p_0}, g/kg	q_a, g/kg	U, m/sec	l_b, m	P_0, mb
2/10/71	0653	2.5	303.2	262.8	21.2	0.87	11.6	2.3	1012.6
1/28/71	0932 to 1030	2.5	308.0	270.0	26.7	2.10	8.7	4.9	1005.8
3/2/71	1010 to 1050	2.5	209.7	280.3	17.1	4.54	7.3	3.8	1002.4
3/4/71	0640 to 0720	2.5	298.7	266.0	16.7	1.88	7.0	8.1	1002.5
9/7/72	0704	3.6	310.7	292.0	30.9	12.60	8.0	3.7	966.8
9/7/72	0900	3.8	315.7	293.7	37.9	13.00	5.0	18.0	968.9
9/12/72	0710	3.9	309.7	295.4	29.5	12.67	9.0	2.0	968.2
9/13/72	0800	2.3	309.9	295.5	29.8	14.13	8.0	1.7	968.9
9/14/72	1022	2.8	314.3	297.0	35.6	15.83	8.0	2.5	973.2

SECTION 6

STACK PLUMES

6.1 PLUME BEHAVIOR

6.1.1 Plume Rise

Vertical motion of the plume to the height where it becomes horizontal is known as plume rise. It is assumed to be a function primarily of the emission conditions at the stack, primarily exit velocity and temperature. The exit velocity gives the flue gases an upward momentum, causing the plume to rise until atmospheric turbulence disrupts its integrity stopping the vertical motion. This is known as the momentum plume rise. Stack gas temperatures are usually much higher than ambient, so that the emissions are less dense than the surrounding air. Such differences in density give the stack gases buoyancy, allowing the plume to rise until it is cooled by the atmosphere, and the density differential becomes zero. This is known as the thermal plume rise.

Momentum and thermal plume rises combine to produce the plume rise of the emitted stack gases. These effects are interdependent. Gases with high exit velocities are cooled faster due to more atmospheric mixing of plume, thus reducing thermal buoyancy. Low exit velocities cause the plume to become trapped in the turbulent wake along the side of the stack and to fall rapidly to the ground (fumigation). Fumigation can usually be prevented by keeping the exit velocity greater than 10 m/sec. An emission velocity that is 1.5 times greater than the atmospheric crosswind is generally accepted as a permissible safety factor to prevent this fumigation phenomenon. Momentum contribution to plume rise is usually insignificant compared to the buoyancy contribution.

Meteorology and the power plant operating characteristics play important roles in determining the height to which pollutants rise and disperse. Wind speed, wind shear and eddy currents influence the interaction between the plume and atmosphere. Ambient temperatures affect the buoyancy of a plume.

6.1.2 Long Range Transportation

The transportation process is considered on three levels:

1. The near-source or single-plume dispersion problem
2. The multiple plume dispersion problem
3. The long-range transportation

Recent studies have attempted to explain single-plume dispersion by modeling techniques, multiple plume dispersion within the context of urban diffusion, and long-range transportation mainly as a meteorological problem. Fox (1) developed an approximate transportation model which is used to calculate the ambient concentration of SO_2 throughout the U.S.

Observations show that pollutants from large emission sources may cause significant air concentrations 800 km to 1600 km (500 to 1000 miles) away. Very high acid precipitation occurs during such periods. The scavanging is often intensified by the topography (1). Milan and Chung (2) have detected the stack plume from the 300 m high Sudbury smelter about 400 km away from its source. An unusually high SO_2 reading over the northern edge of Toronto (Canada) obtained by a correlation spectrometer (COSPEC) remote sensor, and the findings of posterior trajectory analysis of the air parcel over Toronto at the time of measurement provide bases for Milan and Chung's observation. They estimated the total length of the visible plume as approximately 80 km to as high as 160 km.

6.1.3 Effect of Terrain

Bowers and Cramer (3) have studied the plumes from the Mitchell and Kammer (Units 1 & 2) power plants located in complex terrain, 2 km apart in the Ohio Valley, Marshall County, West Virginia. The fixed stack parameters are given in Table 6-1.

Predicted or calculated plume rises from the Briggs equation were in agreement with the observations for the plume from the Mitchell and Kammer No. 1 units. In every case, the predicted plume rise for Kammer No. 2 exceeded the observed rise. This was due to the interaction of this plume with the terrain between the stack and the aircraft observations. These aircraft observations agree well with the measured concentrations near the stack.

An appraisal of the current research in power plant stack plumes in complex (hilly or mountainous) terrain indicated that turbulence is enhanced over complex terrain through thermal drainage, up-slope flows, lee waves and channeling (4). Evidence exists that horizontal spreading of plumes is amplified in complex terrain to a greater extent than vertical spreading. Available models tend to over-predict plume concentrations by factors of five or more at distances within a few kilometers of the source, but model predictions improve at greater distances. The models, in general, underestimate the initial lateral spread of the plume and overestimate vertical spread at greater distances. In other words, the observed plume in complex terrain (compared to flat terrain for similar stability conditions) has a larger cross-section, and the plume is generally more dilute in the core by a factor of two or more (5).

6.2 STACK GAS COMPOSITION

6.2.1 Introduction

Sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), and a variety of aliphatic organic compounds constitute the major atmospheric emissions from fossil-fueled power plants. In addition, significant amounts of trace metals and metalloids, acid mists and polycyclic organic species are also emitted. Table 6-6 shows the average air pollution emissions from various power plants according to fuel type (6).

The amount of SO_x emitted from a power plant is directly related to the sulfur content of the fuel used. The average sulfur content of U.S. coals is about 2.5%, and the residual fuel oils contain between 0.7 and 5.5% of sulfur in the form of dissolved H_2S, elemental sulfur and organic sulfur compounds. Natural gas is typically very low in sulfur which is present primarily as H_2S.

About 95% of the sulfur present in fossil fuels is emitted in the form of sulfur oxides. Due to the reversible and temperature dependent nature of the conversion reaction, only 1-2% of the sulfur is emitted as SO_3 which rapidly reacts with water vapor to produce sulfuric acid. SO_2 concentrations appearing at the stack exit typically lie in the range 500 to 3000 ppm, with 1000 to 2000 ppm being common without controls.

The extent of nitric oxide, NO, formation depends primarily upon the O_2 and N_2 contents of the feed air, the combustion temperature and the average residence time of the oxygen and nitrogen molecules in the combustion zone. The amount of nitrogen dioxide, NO_2, formed during combustion is generally much less than that of nitric oxide (NO) and depends on the amount of NO formed and thus on the combustion temperature. Actual concentrations of NO_x are normally in the range of 300 to 1300 ppm in the stack emissions.

Particulate emissions from coal-fired power plants are much higher than that emitted by oil- and gas-fired plants as shown in Table 6-6. These particles contain a wide variety of toxic trace elements including metals, metalloids and organic species. The major elemental constituents of coal fly ash are silicon, aluminum, iron, potassium and calcium (Table 6-7).

As many as 37 trace elements have been found in coal (Table 6-8). These are transferred to slag, fly ash or flue gases on combustion. The specific concentrations (ug/gm) and volume concentrations (ug/m^3) of the trace elements in coal and oil fly ash are given in Table 6-9. This comparison indicates that fly ash is more prevalent from coal than from oil.

Other emissions from fossil fueled power plants include: gaseous hydrocarbons, aldehydes, and sulfuric and hydrochloric acid mists. Sulfuric and sulfurous acid mists are formed in small amounts near the exit of power plant stacks where the temperature is sufficiently low to allow formation of liquid water droplets which absorb SO_2 and SO_3. Some metal-catalyzed oxidation of sulfite to sulfate takes place in these droplets which are extremely acidic and corrosive (6).

With various technologies and fuels available for steam production, no standard composition can be assigned to stack gases (Tables 6-2 to 6-5). For instance, sulfur contents between Western coal and Eastern coals vary widely; neither is the sulfur content in oil from different regions uniform. To complicate matters further, trace elements such as iron significantly affect certain reactions. Particulates also have a significant impact on the chemical reactions. For example, large particulates are believed to mitigate acid production resulting from stack gases (7). Smaller particulates may enhance chemical reactions or have no influence at all. With different particulate inhibitors such as electrostatic precipitators and various load conditions, the particulate size distribution emitted by a stack varies from .01 - 100 um (3). Different technologies create different reactions and particulate distributions within the boiler because of different flame temperatures, feed air and air cleaning processes. Consequently, individual plant stack studies are necessary to accurately represent stack gas composition.

Fuel composition is the most important factor determining stack gas composition. The literature appears to analyze coal more than oil or natural gas. However, both oil and coal, which are the major fuel sources for electric steam generation, are dealt with in this report. In general, Western U.S. coal has higher ash content and exhibits higher alkaline earth metal contents. SiO_2, Al_2O_3, CaO and Fe_2O_3 are major constituents by far in western coals. Because of the higher concentration for CaO and Na_2O in the fly ash, Western coal is more alkaline than Eastern coal (8). Some of these constituents act as catalysts in sulfate formation, particularly Fe_2O_3. In both coal and oil, about 95% of the sulfur is emitted as SO_2 with sulfates usually amounting to 1 or 2%.

This information gives the reader a general characterization of stack gas composition. Further details as to their importance in sulfate and acid production will be provided in a later section.

6.2.2 Power Plant Emission Rates

In accordance with Federal New Source Performance Standards, the emissions from fossil-fuel fired generating units of 250 x 10^6 Btu/hr or more heat input must be expressed in terms of lb/10^6 Btu heat input. Pollution concentrations, effluent volumetric flow rate, and heat input rate (fuel rate x fuel heat content) are required to calculate emission rates. An alternative method using pollution concentrations is presented by Shigehera (9). This method uses a ratio F, which is the effluent gas generated per 10^6 Btu heat content. Average F factors for various fossil fuels are given in Table 6-10.

Nitrogen-based anthropogenic emissions are responsible for as much as 30-40% of the strong-acid anion found in low pH samples in the U.S. However, characterization of NO_x emissions is more complex than SO_2. Of the approximately 24 million tons of NO_x emitted annually, 45% is from industrial and power-generation point sources, while 36% is from transportation sources. In comparison, stationary point sources and area sources emitted 87% and 13%, respectively, of the 32 million tons of SO_2 emitted annually in the United States. Both active photochemical reactions and mobile sources complicate and make the assessment of NO_x pollution levels very difficult (1).

6.2.3 Sulfur Dioxide and Conversion to Sulfates

Other than particulates, sulfur oxides and nitrogen oxides are the major air pollutants emitted from stacks in coal-fired plants. These oxides undergo thermochemical oxidation with the water vapor from cooling tower plumes and form basic ingredients for further interaction. This section summarizes the review of available literature on these topics.

Literally hundreds of articles dealing with this subject are available. Thus, it is not the intent of this report to make a comprehensive review of SO_2, oxidation or atmospheric sulfates. Such studies have already been completed (10). EPA has completed studies and has prepared a position paper on Regulation of Atmospheric Sulfates (EPA-450/2-75-007, September 1975, NTIS PB-245760). Some of the salient information pertinent to the interaction phenomenon is presented here.

The literature reviewed on the oxidation of SO_2 to sulfate in power plant plumes does not lead to firm quantitative conclusions regarding rates of conversion or the mechanisms involved (11) (Table 6-11).

Studies dealing with sulfur oxidation processes in stack plumes have estimated the rates range from 0 to 50%/hr. However, the bulk of literature supports a rate somewhere between 0.5 to 10%/hr with a reasonable value for many situations being 2%/hr (10). Several factors affect the rate of oxidation: meteorological conditions, catalytic chemicals in the stack gas, and background chemicals. Photochemical reactions are significant with regard to background. Photochemical reactions caused by the stack plume itself affect oxidation rates further downwind rather than over the short term. In nearly all instances, oxidation from the stack gas occurred within a few kilometers (12), with a high oxidation rate near the stack and a lower rate downwind (10). However, recent studies indicate lower rates than previously reported (10). In coal-fired stack gas plumes, oxidation seldom exceeded 4% - one third of which came from combustion. On the other hand, for oil-fired plumes, the oxidation was measured at twice the amount of the coal-fired plume. This difference may be due to "plume dropout" which is particulate precipitation of sulfur (12). MacKenzie (13) maintained that 10 to 20 miles downwind the oxidation rate accelerates, and SO_2 oxidation is rather slow under stable meteorological conditions during the first 10 miles or so. The SO_2 plume centerline concentration will change only by about 0.2 ppm over about 20 miles so that oxidations can therefore be significant downwind. A later paper by Forrest et al. (14), stated that the extent of SO_2 oxidation as measured by aircraft seldom exceeded 5% with essentially all oxidation within the first few kilometers. This contrasts with the oil-fired plume in which 20% oxidation occurred.

Meteorological factors such as temperature and relative humidity affect oxidation rates. Given equal conditions of other criteria, increased relative humidity and temperature both mean increased oxidation rates. A numerical model by Freiberg (15) of oxidation as a function of the emission and the iron catalytic reactor depicts oxidation as a function of dispersion, relative humidity and temperature. However, the contention of Forrest and Newman (14) directly conflicts with this model. No obvious correlation between temperature or relative humidity and the oxidation rate was found by Forrest and Newman. In addition, there is insufficient evidence in field experiments to support Freiberg's model.

Forrest and Newman of Brookhaven National Laboratories employed a $^{34}S^{32}S$ isotope ratio and particulate sulfur to total sulfur concentration ratios to determine the percent of SO_2 converted to sulfates in the plumes of several oil and coal-fired power plants (12,14). The plants studied are included in Table 6-12.

The extent of oxidation in oil-fired plumes (26%/hr) was more than triple that observed for coal (8.5%/hr), indicating that significant amounts of sulfate were dropping out of the plumes. This might cause observations of sulfate formation to appear to be less than their true values (12).

In summary, these studies indicated a heterogeneous mechanism for the oxidation of sulfur with the consumption or poisoning of available catalyst. No distinct correlation was found between the extent of SO_2 conversion with distance, travel time, temperature, relative humidity, time of day or atmospheric stability.

Plume reproducibility measurements showed that the plume can vary from moment to moment by as much as a factor of two in percentage of total sulfur as particulate sulfur (14).

If the isotope results are discarded (the isotope technique is considered erroneous by Wilson), Forrest and Newman's data indicated that no difference exists between oil- and coal-fired plumes and that depending on conditions, sulfur conversion rates of substantially greater than 1% per hour are possible.

Freiberg (15) developed a model which depicts quantitatively the iron catalized oxidation of SO_2 to acid sulfate mist in dispersing stack plumes and indicated that:

1. Relative humidity and temperature strongly influence the rate of oxidation.
2. Not all of the SO_2 emitted will be converted to H_2SO_4.
3. Most of the oxidation always happens during the first hour of plume travel and usually in considerably less time.
4. A maximum value of (SO_4^{2-}) is obtained at a downwind distance which depends upon atmospheric parameters.
5. Ammonia from air is needed as a buffer to enable the oxidation to proceed in the droplets.
6. No appreciable oxidation occurs below pH = 2 as observed by Junge and Ryan.

Brosset (16) proposed a model for the catalytic oxidation of sulfur dioxide in aqueous solution which is related to acidification of rain, based on the assumption that a catalytic ion and hydrogen sulfite ions form a sparingly soluble solid phase. This phase is oxidized by oxygen as soon as it is precipitated, resulting in the formation of sulfate ions and the dissolution of the solid phase. This model adequately explains the wet deposition of sulfate resulting from sulfur dioxide emissions.

Garland and Branson (17) studied the SO_2 concentrations over Great Britian and reported that a value of 1200 m is the mean mixing height for SO_2. This indicates that dry deposition limits the mean lifetime of SO_2 to about 40 hours.

Enviroplan (18) conducted a study to predict the maximum annual average, 24-hour and 3-hour SO_2 concentrations produced annually by a new modern 1000 MWe hypothetical electric power plant that complies with the Federal New Source Performance Standards for SO_2 emissions from coal-fired power plants. A total of three plant alternatives were examined: Case One, the use of a scrubber; Case Two, the use of a scrubber with reheat of scrubbed gases before stack emissions; and Case Three, the use of low sulfur coal. All cases used a 400-ft stack height in the analysis. The meteorological data used in the study were obtained from hourly observations at the Youngstown Airport in Youngstown, Ohio for the year 1973.

Table 6-13 summarizes the findings of the Enviroplan study and shows that Case One had the worst SO_2 concentrations among the 3 cases. These results are dependent on factors such as power plant size, fuel burned, meteorological conditions and stack heights utilized. For a 2000 MWe power plant with a single 400-ft stack, the maximum 24-hour SO_2 concentration for Case One will be less than twice that of a 1000 MWe plant. The concentrations will be within the government limitations, vis., 100 ug/m^3 and 750 ug/m^3, respectively for maximum 3-hour and 24-hour SO_2 concentrations.

The American Electric Power Service Corporation and the Ohio Edison Corporation continuously monitor the ground-level concentrations of sulfur dioxide at several monitoring sites. Considering the meteorological conditions and electric generation in the Upper Ohio Valley, it appears that the power plants did not adversely affect the ground-level SO_2 concentrations as had been expected under the influence of an air stagnation episode. Examination of a large number of stagnation episodes occurring over a period of two to three years bears out the findings of this study.

6.2.4 NO_x and Ozone

Field studies of the plumes from two coal-fired plants (Pacific Power and Light Plant at Centralia, WA and the Four Corners Plant at Farmington, NM) and two gas-fired power plants (Cunningham Plant at Hobbs, NM, and the Wilkes Plant at Longview, TX) were made by Hegg *et al.* (19). Airborne measurements were made of the concentrations of NO, NO_2, O_3 and SO_2, temperature, relative humidity and ultraviolet radiation. Data was collected in 30 flights over an eight-month period. Ozone concentrations exceeding those of the surrounding ambient air were never found in these plumes, which were observed to distances of 90 km (4 hours travel time) from the stacks. Analysis of the plume chemistry suggests that over distances and time scales within which plumes are differentiable from background (the "near-field"), the chemistry is commonly controlled by the rates at which the plumes mix with the ambient air, rather than by chemical kinetics. Consequently, the rates of conversion of NO to NO_2 are slow and the NO_2/NO ratios are small (the highest ratio measured was 4.3). This analysis is consistent with the observation that ozone was not generated in the power plant plumes.

Thirty sets of airborne measurements have been obtained by Kornberg et al.(20) in the plumes from two coal-fired and two gas-fired power plants situated in different climatological areas. The amount of ozone in power plant plumes was not greater than ambient ozone to distances at which the plume was still distinguishable from the ambient air. These field observations are understandable if the following observations are considered. The precursors of ozone in fossil-fuel power plants are nitrogen oxides, primarily nitric oxide. Nitric oxide must be converted to nitrogen dioxide in the plume before ozone can be produced. Field data analysis reveals that this conversion rate is generally controlled by the rate at which a plume mixes with the ambient air rather than by the relevant chemical reaction rates. Since this mixing rate is slower than the chemical reaction rates for the production of ozone, the conversion of nitric oxide to nitrogen dioxide (and hence to ozone) is slower than would be expected from laboratory or smog chamber experiments. Thus, the conversion rates are slow enough to make ozone production in power plant plumes unlikely.

In studies of a large, coal-fired power plant, ozone concentrations within the plume were depressed below background levels (21). In all traverses (to 45 km downwind), the depth of this ozone deficit and the ratio of NO to NO_x in the plume both decreased with increasing distance from the plant. A model which accurately predicted the observed plume profiles of O_3, NO, and NO_x from the background conditions, plume geometry, and basic photolytic cycle indicated that free-radical reactions within the plume did not significantly affect oxidant concentrations at the distances sampled. Data on NO, NO_2, O_3 and SO_2 in the plume of a 1000 MWe power plant firing a mixture of oil and coal revealed a drop of ozone concentration in the plume boundaries and indicated that at 50 km downwind there was an increase in ozone (the bulge) coincident with low levels of plume SO_2 (10).

Recent airborne measurements, designed to facilitate understanding the chemistry and physics of plumes from fossil power plants, suggest that ozone may be found in power plant plumes in concentrations exceeding background levels, although most studies indicate no ozone buildup in plumes (22). Further studies are required to explain the observed ozone buildup in plumes.

In general, ozone is expected to enhance SO_2 oxidation. However, in urban areas, the existence of O_3 was not observed in the stack plumes during short range field studies (10,19,20,23). There may be O_3 production in stack plumes further downwind or on a regional scale (10,23). However, field studies indicated that no net ozone production in power plant plumes resulted from entrainment of ambient ozone (23). Where hydrocarbon and NO_x emission are already present, such as in urban areas, SO_2 oxidation from ozone becomes feasible.

Forrest and Newman (14) stated that no evidence existed for increased SO_2 conversion even at the fringe of plumes. NO_x within the plume depletes ozone and thereby the SO_2 oxidation rate near the stack is lower than downwind (10, 13). However, nitrogen oxides - ozone chemistry is not well established. The analysis of the NO_x-O_3 chemistry (24) at four power plants indicated the plume chemistry is generally diffusion controlled out to distances measured (90 km). The NO to NO_2 conversion rates and NO_2/NO ratios were consequently lower than expected from chemical kinetics alone. The consensus is that net ozone production does not occur within the stack plume; hence, there is no evidence for increased SO_2 conversion.

6.2.5 Acid Precipitation

Acidity of rainwater is of concern due to the progressive acidification of soils, its effect on flora and fauna, and its corrosiveness to metals (25). Acidic precipitation (rain, snowfall, mist, fog, etc.) in a local area could be, to some degree, contributed by the interaction of the cooling tower plume with the stack effluents.

In general, little data is available on the mechanism of acid production leading to precipitation in the atmosphere (22). Problems relate to the understanding of sulfur chemistry within the atmosphere. Nitrogen acids are believed to contribute between 25-40% of the atmospheric acid. However, the contribution from individual power plants has not been studied. The information presented in this section, although not exhaustive, is intended to give a general description of available data on acid precipitation. It is assumed that the acidity of rainwater is due to formation of strong acids and is a result of the atmospheric interaction of pollutants, especially SO_2 and NO_x, emitted by electric power generating plants.

Chemical analysis of precipitation samples collected from 10 sites in South Central Maine during June 18, 1974 to September 30, 1974, were used to determine regional deposition patterns of ionic constituents. Acidic pH values ranging from 3.8 to 5.0 were characteristic of the region. Systematic increases in sulfate and sodium deposition in the samples in one site where relatively alkaline pH of 5.5 to 7.0 was observed suggest the influence of a local source. The composition of precipitation near a Kraft paper mill indicates influence of background levels up to 20 km from the source (26).

The Allen S. King Generating Plant near Bayport, Minnesota delivers 420 tons of sulfur dioxide to the atmosphere daily from a 789-ft (240-m) stack. Dispersal from this height theoretically minimizes harmful effects of the stack gases on vegetation. Recorded pH values (pH 4-9) around the power plant were not significantly different from values obtained in several other localities in Minnesota (27).

Analysis of recent precipitation samples from the Northeastern United States showed a pH consistently less than 4.4 when the expected pH based upon equilibrium with CO_2 would be 5.6, attributing 65% of the acidity to H_2SO_4, 30% to HNO_3, and less than 5% to HCL. The pH values may be predicted from chemical content and generally agree with the observed pH to within 0.1 pH unit. The pattern of acid precipitation apparently has existed since about 1950-1955, but the intensity of acid deposition, especially due to HNO_3, has increased since then. Analysis of prevailing winds indicates that much of the acidity originates as a general source over industrial areas in the Midwest (28).

Precipitation chemistry data from the 1920's indicates heavy ionic deposition, but low acidity (calculated) in Tennessee (pH 7.4) and New York (pH

6.15). Summer acidity is currently lower in Tennessee than in the Northeast. Precipitation chemistry of individual storms reveals some local variation even within a 93 km range, but a storm in central New York is generally homogeneous over 70 km (29).

Studies to determine factors affecting composition of acidic precipitation formation in the Austin area of Central Texas showed normal rainfall pH values of 6.5 to 6.6 in the area, with extreme variations from 5.8 to 7.3 (30). Significant calcium levels of 1-4 mg/l were observed, probably of natural origin, and appeared to have a buffering effect on acidity. Significant sulfate and nitrate ion concentrations occurred during the early stages of rainfall where the rainfall pH was dependent on the calcium-sulfate ratio.

An experimental study of the kinetics of a reaction system containing micromolar quantities of SO_2, NH_3 and particulate matter in the presence of a relatively large amount of water indicated that very strong acids such as dithionate ion, sulfate and bisulfate ions were formed if the observed pH values of 4 to 5 were theoretically justified (25).

Detailed chemical analyses revealed that acid precipitation (pH approximately 5.6) in the Northeastern United States was caused by the strong mineral acids; namely, sulfuric and nitric acid (Table 6-14). There is a large array of other proton sources in precipitation, weak acids and Bronsted acids; however, although these other acids contribute to the total acidity of precipitation, they have a minimal influence on the free acidity (ambient pH) of acid precipitation (31).

Rain and snow were collected in plastic beakers either manually or with a Wong sampler during 58 precipitation events in 1974 at Yonkers, New York, approximately 24 km north of the center of New York City. Determinations were made of total dissolved ionic species, free hydrogen ions, total hydrogen ions, sulfate, nitrate, chloride and flouride. Conductivity measurements ranged from 162 to 618 umhos, pH from 3.4 to 4.9, total acidity from 36 to 557 ueg/l, sulfate from less than 1 to 20 mg/l, nitrate from less than 1 to 14 mg/l, chloride from less than 1 to 7 mg/l and flouride concentrations less than 0.1 mg/l. These results indicated that precipitation at a suburban location adjacent to New York City was consistently acidic and contained concentrations of sulfate, nitrate and chloride, which were similar in values found for other locations in the Northeastern United States (32).

Rainwater samples possess a time-dependent pH which can be correlated with the surface wind trajectories (33). Standard procedures for determining the pH of rain samples usually involve substantial delays from the time of rainfall to the time of analysis. This assumes that no change in pH occurs during the storage period, although this is not always true.

Particulates have some effect on acidification in the atmosphere. For example, particulates emitted from a stack with no controls can act as a buffer (4). Jones (34) stated that fly ash buffers acid. However, these conclusions may be the result of unique cases since another study supports the belief that the particulates increase chemical reaction rates: the surface area increases as r^2 and the number of particles increases the rates (8).

The electrostatic precipitator is less efficient for smaller particles than for larger ones so that there are about a million more .01 um than 1 um particles. Because the surface area of 1 um particles is 10^4 larger, Ananth et al.(8) stated that the number of particles was more significant to increased reactions than the increase in area. In addition to providing a surface area for sulfate formation, the particulates also act as catalysts. These particulates contain oxides of Fe, Ca, Na, Mg, Pb, V and Cd, and when they come in contact with SO_2 and sulfates, they act as catalysts for chemical reactions (8) either to neutralize (Ca, Mg) or produce (Fe, Pb, V, Cd, Na) acid (34).

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TABLE 6-1

FIXED STACK PARAMETERS (3)

Parameter	Mitchell	Kammer No. 1	Kammer No. 2
Stack Exit Temp. (^{o}K)	441.3	441.3	441.3
Stack Height (m)	365.8	183.2	183.2
Stack Diameter (m)	10.66	4.75	3.35
Plant Elevation Above MSL (m)	210	197	197

TABLE 6-2

TRACE AND MINOR ELEMENT STACK EMISSION (35)
(lb/yr-1000MW)

Station:	Station I	Station II	Station III
Coal Type:	Sub-bituminous	Sub-bituminous	Lignite
Emission Control:	Venturi Scrubber	Electrostatic Precipitator	Cyclone Separator
Element			
Aluminum	390,000	350,000	6,900,000
Antimony	41	33	1,800
Arsenic	500	8.2	11,000
Barium	9,800	<3,000	<70,000
Beryllium	29	<50	280
Boron	16,000	10,000	630,000
Cadmium	190	18	650
Calcium	1,300,000	610,000	17,000,000
Chlorine	430,000	330,000	410,000
Chromium	18,000	6,500	41,000
Cobalt	310	170	2,900
Copper	1,400	1,400	20,000
Fluorine	20,000	31,000	350,000
Iron	210,000	110,000	8,800,000
Lead	1,200	670	3,500
Magnesium	210,000	90,000	4,200,000
Manganese	5,300	2,000	68,000
Mercury	530	190	960
Molybdenum	8,600	350	33,000
Nickel	2,400	3,300	30,000
Selenium	410	1,400	3,300
Silver	17	4.1	<40
Sulfur	28,000,000	27,000,000	83,000,000
Titanium	19,000	24,000	190,000
Uranium	140	35	1,400
Vanadium	9,800	2,900	28,000
Zinc	6,000	940	33,000
Fly Ash	3,900,000	2,900,000	97,000,000

TABLE 6-3

PARTICULATE EMISSION TEST RESULTS (36)

Utility	Test No.	Firing Condition	Av. Gr/SCF @ Std. Cond.	lb./10^6 BTU	Grams/ 10^6 cal.	Reqd. Efficiency to Meet 0.1 lb./ 10^6 BTU	% Carbon of Particulate	Coal Ash Wet, %	HHV BTU/lb. Wet
TVA	1B	Base **	4.46	5.32	9.58	98.12	13.04	14.64	11,281
	1C	Base **	4.45	5.33	9.59	98.12	9.11	18.27	10,258
	12C	Low NO_x	3.80	4.56	8.21	97.81	6.21	12.30	10,622
	12D	Low NO_x	3.55	4.26	7.67	97.65	8.08	12.30	10,622
So. Elec. Gen. Co.	28A	Base	4.93	6.18	11.12	98.38	2.69	15.00	11,690
	28B	Base	4.55	5.70	10.26	98.25	1.09	15.00	11,690
	29	Base	3.80	4.72	8.50	97.88	1.69	16.06	11,461
	30	Base	3.78	4.75	8.55	97.89	2.01	13.28	11,398
	26	Low NO_x	4.46	5.48	9.86	98.18	5.65	12.12	11,752
	27A	Low NO_x	4.68	5.75	10.35	98.26	3.37	9.84	11,632
	27B	Low NO_x	6.02	7.39	13.30	98.65	4.08	9.84	11,632
Salt River Project	3B	Base	3.17	4.27	7.69	97.66	.92	11.49	10,210
	2A	Base	3.48	4.27	7.69	97.66	1.79	5.94	11,068
	3D	Base	1.93	2.50	4.50	96.00	1.98	6.04	11,186
	18B	Low NO_x	4.95	6.26	11.27	98.40	.80	11.49	10,210
	18C	Low NO_x	5.35	6.85	12.33	98.52	1.16	6.62	10,780
	18E	Low NO_x	2.36	2.87	5.17	96.52	1.53	6.04	11,186
Pub. Ser. Co. of Colorado	30	Base	2.56	3.11	5.60	96.79	.66	*	*
	33	Base	2.59	3.18	5.72	96.86	.55		
	27A	Low NO_x	1.85	2.26	4.07	95.58	.46		
	27B	Low NO_x	2.41	2.94	5.29	96.60	.18		
	34	Low NO_x	1.96	2.34	4.21	95.73	.50		
	35	Low NO_x	2.02	2.41	4.34	95.85	.59		

* Analyses not available at this time

** Normal firing but at lower than normal excess air levels

TABLE 6-4

AIHL ANALYSES OF SULFUR, VANADIUM AND FLY ASH CONTENTS OF FUEL OILS BURNED DURING STUDY (36)

Date	Power Plant	% S (w/w)	% Ash (w/w)	V, ppm (w)	V as % of Ash
9-10-74[a]	Moss Landing	0.35 ± .03	0.027 ± .002	13.0 ± 3.4	5.0
9-11-74[a]	Moss Landing	0.40 ± .006	0.016 ± .001	13.4 ± 1.3	8.4
9-12-74	Moss Landing	Burned Natural Gas			
10-01-74[b]	Haynes	0.45 ± .01	0.0075 ± .0007	9.1 ± .5	12
10-04-74	Haynes	0.45	0.008	11.3	15
10-11-74[b]	Haynes	0.46 ± .01	0.0075 ± .0007	10.7	14
10-17-74[b]	Haynes	0.455 ± .005	0.0075 ± .002	10.6 ± 1.1	14
10-25-74	Edison	0.44	0.007	14.5	21
10-30-74	Edison	0.45	0.006	13.4	22
11-07-74	Edison	0.45	0.012	20.5	17

a. Analyses shown for this date are means for 6 samples.

b. Separate samples taken for each of two boiler units operating on sampling day. Values shown are means for the two units.

TABLE 6-5a

TRACE METALS IN FLY ASH AS A FUNCTION OF PARTICLE SIZE (8)

Particle Size:	Concentration, ppm 25 um	 12.5 um	 10 um	 3.5 um	 1.5 um
Element					
Al	67,000	54,300	57,300	63,600	59,300
B	300	500	500	500	500
Be	2	1	2	2	2
Cd	≤5	≤5	≤5	≤5	100
Cr	130	130	130	300	300
Cu	150	150	200	200	200
Fe	40,000	59,000	43,500	35,500	32,300
Mn	200	240	290	390	500
Ni	300	200	200	300	300
Pb	300	200	300	300	500
V	200	200	300	200	200

---

a/ Sample collected from a coal-fired steam power plant and analyzed by neutron activation and spark source mass spectrometry.

TABLE 6-5b

CONCENTRATION AND SIZE OF TRACE METAL PARTICLES IN URBAN AIR (8)

Metal	Concentration (ug/m^3)	MMD[a/] (um)	Particles < 1 um (%)
Fe	0.6 -1.8	2.35-3.57	12-35
Pb	0.3 -3.2	0.2 -1.43	59-74
Zn	0.1 -1.7	0.58-1.79	14-72
Cu	0.05 -0.9	0.87-2.78	16-61
Ni	0.04 -0.11	0.83-1.67	28-55
Mn	0.02 -0.17	1.34-3.04	13-40
V	0.06 -0.86	0.35-1.25	41-72
Cd	0 -0.08	1.54-3.1	22-28
Ba	0 -0.09	1.95-2.26	20-31
Cr	0.005-0.31	1.5 -1.9	45-74
Sn	0 -0.09	0.93-1.53	28-55
Mg	0.42 -7.21	4.5 -7.2	17-23

---

a/ The mass median diameter (MMD) represents the approximate "average" aerodynamic particle size, i.e., 50% of the particles are above this size and 50% are below.

Note: The unit symbolized by "um" is a micron, i.e., 10^{-6} meters. Accordingly "ug" represents a microgram.

TABLE 6-6

AVERAGE AIR POLLUTION EMISSIONS FROM VARIOUS POWER PLANTS (6)

(Values are presented as g/kg of fuel)

Fuel	Particles*	CO	HC	NO_x	SO_x**	HCOH
Coal	85 (1-E)	0.25	0.1	10	19S	0.002
Oil	1.7 (1-E)	0.07	0.5	17	19S	0.1
Natural Gas	2.7 (1-E)	negl.	negl.	70	19S	0.2

* E is the mass collection efficiency of the control equipment.

** S is the percent sulfur content of the fuel by weight.

TABLE 6-7

TYPICAL COMPOSITION OF COAL FLY ASH (6)

(Weight Percentages of Oxides)

Major Constituents

Al_2O_3	SiO_2	$FerO_3$	K_2O	CaO
14-30	22-60	3-21	.2-3.5	.5-31.0

Minor Constituents

Li_2O	Na_2O	MgO	TiO_2	P_2O_5	SO_4*
.01-.07	.2-2.3	.7-12.7	.6-2.6	.1-1.1	.1-2.2

* Soluble Sulfate

TABLE 6-8

CONCENTRATIONS AND CONCENTRATION RATIOS FOR 1973 RUNS ON DIFFERENT FOSSIL FUEL COMPONENTS (6)

	Element Concentration, ppm				Concentration Ratios		
Element	Coal	Slag	Inlet Fly Ash	Outlet Fly Ash	Slag/ Coal	(Inlet fly ash)/ slag	(Outlet fly ash)/ (inlet fly ash)
Al	10,440	102,300	90,900	76,000	9.8	0.9	0.8
At	4.45	18	110	440	3.6	6.1	4.0
Ba	65	500	465	750	7.7	0.9	1.6
Br	3.7	2	4	---	0.5	2.0	-
Ca	4,340	46,000	25,200	32,000	10.6	0.5	1.3
Cd	0.47	1.1	8.0	51	2.3	7.3	6.4
Ce	8.2	84	84	120	10.2	1.0	1.4
Cl	914	100	200	---	0.1	1	-
Co	2.9	20.8	39	65	7.2	1.9	1.7
Cr	18	152	300	900	8.4	2.0	3.0
Cs	1.1	7.7	13	27	7.0	1.7	2.1
Cu	8.3	20	140	---	2.4	7.0	-
Eu	0.1	1.1	1.3	1.3	11.0	1.2	1.0
Fe	10,850	112,000	121,000	150,000	10.3	1.1	1.2
Ga	4.5	5	81	---	1.1	16.2	-
Hf	0.4	4.6	4.1	5.0	11.5	0.9	1.2
Ho	0.122	0.028	0.050	---	0.2	1.8	-
K	1,540	15,800	20,000	24,000	10.3	1.3	1.2
La	3.8	42	40	42	11.0	1.0	1.0
Mg	1,210	12,400	10,600	---	10.2	0.9	-
Mn	.8	295	298	430	8.7	1.0	1.4
Na	696	5,000	10,100	11,300	7.2	2.0	1.1
Ni	16	85	207	---	5.3	2.5	-
Pb	4.9	6.2	80	650	1.3	12.9	8.1
Rb	15.5	102	155	190	6.6	1.5	1.2
Sb	0.5	0.64	12	55	1.3	18.8	4.6

TABLE 6-8 (cont'd.)

	Element Concentration, ppm				Concentration Ratios		
Element	Coal	Slag	Inlet Fly Ash	Outlet Fly Ash	Slag/ Coal	(Inlet fly ash)/ slag	(Outlet fly ash)/ (inlet fly ash)
Sc	2.2	20.8	26	36	9.5	1.2	1.4
Se	2.2	.080	25	88	0.0	310	3.5
Si	23,100	229,000	196,000	---	9.9	0.9	-
Sm	1.0	8.2	10.5	9	8.2	1.3	0.9
St	23	170	250	---	7.4	1.5	-
Ta	0.11	0.95	1.4	1.8	8.6	1.5	1.3
Th	2.1	15	20	26	7.1	1.3	1.3
Tu	506	4,100	5,980	10,000	8.1	1.5	1.7
U	2.18	14.9	30.1	---	6.8	2.0	-
V	28.5	260	440	1,180	9.1	1.7	2.7
Zn	46	100	740	5,900	2.2	7.4	8.0

TABLE 6-9

SPECIFIC CONCENTRATIONS (ug/gm) AND VOLUME CONCENTRATIONS (ug/m^3) OF TRACE ELEMENTS IN COAL AND OIL FLY ASH (6)

	Coal Fly Ash		Oil Fly Ash	
Element	ug/gm	ug/m^3	ug/gm	ug/m^3
As	10-500	60-90	30	5
Ba	100-1000	30-110	9000	1600
Be	1-10	--	--	--
Cd	10-100	--	--	--
Co	10-100	1-5	90	16
Cr	10-1000	8-20	66	12
Cu	10-1000	--	--	--
Hg	0.1-1.0	--	--	--
Mn	100-1000	12-40	45	8
Mo	10-100	--	--	--
Ni	10-1000	10-25	--	--
Pb	100-5000	10-15	--	--
Sb	1-100	1-2	5	1
Se	10-100	8-18	5	1
Sn	1-10	--	--	--
V	50-5000	5-60	100-100,000	1000-1200
Zn	1000-10,000	20-70	3500	640

Note: The unit symbolized by "ug" is a microgram, i.e., 10^{-6} grams.

TABLE 6-10

AVERAGE F FACTORS FOR VARIOUS FOSSIL FUELS (9)

Fuel	F Factor, scfd/10^6 Btu(a)
Coal - Anthracite	101.4
Coal - Bituminous, Lignite	98.2
Oil - Crude, Residuum, Distillate, Fuel Oil	92.2
Gas - Natural, Butane, Propane	87.4

(a) Standard conditions are 70°F, 29.92 in Hg and 0% excess air.

TABLE 6-11

MECHANISMS THAT CONVERT SULFUR DIOXIDE TO SULFATES (11)

Mechanism	Overall reaction	Factors on which sulfate formation primarily depends
1. Direct photo-oxidation	$SO_2 \xrightarrow[\text{water}]{\text{light, oxygen}} H_2SO_4$	Sulfur dioxide concentration, sunlight intensity.
2. Indirect photo-oxidation	$SO_2 \xrightarrow[\text{organic oxidants, hydroxyl radical (OH}^{\cdot}\text{)}]{\text{smog, water, NOx}} H_2SO_4$	Sulfur dioxide concentration, organic oxidant concentration, $OH^{\cdot}$, NO_x.
3. Air oxidation in liquid droplets	$SO_2 \xrightarrow{\text{liquid water}} H_2SO_3$	Ammonia concentration.
	$NH_3 + H_2SO_3 \xrightarrow{\text{Oxygen}} NH_4^+ + SO_4^{=}$	
4. Catalyzed oxidation in liquid droplets	$SO_2 \xrightarrow[\text{heavy metal ions}]{\text{oxygen, liquid water}} SO_4^{=}$	Concentration of heavy metal (Fe, Mn) ions.
5. Catalyzed oxidation on dry surfaces	$SO_2 \xrightarrow[\text{carbon, water}]{\text{oxygen, particulate}} H_2SO_4$	Carbon particle concentration (surface area).

TABLE 6-12

PLANTS STUDIED BY BNL (12,14)

Name of Plant	Capacity, MWe	Fuel Used
1. Port Jefferson Plant, Port Jefferson, N.Y.	467	oil
2. Northport Plant, Northport, N.Y.	1,160	oil
3. Albany Plant, Bethlehem, N.Y.	400	oil
4. Devon Plant, Milford, Connecticut	454	oil
5. Labadie Plant, Missouri	4 x 600	3% Sulfur Pulverized Coal
6. Portage des Sioux Plant, West Afton, Missouri	2 x 500	3% Sulfur Pulverized Coal
7. Muscle Shoals Plant, Alabama (TVA)	5 x 290	Pulverized Coal
8. Kyger Creek Plant, Charleston, West Virginia	1,000	Coal

TABLE 6-13

ENVIROPLAN PLANT OPERATING DATA (18)

	Case One (scrubber)	Case Two (scrubber)	Case Three (low-sulfur coal)
Effective plant size (megawatts)	1000	1000	1000
Stack height (feet)	400	400	400
Stack diameter (feet)	24.4	26.3	24.5
Gas exit velocity (feet/second)	100	100	100
Gas exit temperature	170°F	250°F	300°F
Ratio of density of exit gases to density of ambient air at same temperature	0.9929	0.9929	1.0180
SO_2 emission rate (tons/hour)	5.610	5.786	5.400
Largest annual average SO_2 concentration (ug/m^3)	1.69	0.98	0.95
Maximum 24-hour SO_2 concentration per year (ug/m^3)	55.01	40.69	38.44
Maximum 3-hour SO_2 concentration per year (ug/m^3)	234.28	184.32	173.90
Heat rate (BTU's/KWH)	9350	9644	9000
Pounds of air used[(a)] per lb. of coal burned @ 20% excess air	11.8416	11.8416	11.8416
Total lbs. of coal[(b)] burned per hour	779,167	803,667	750,000
Total lbs. of air used per hour	9.2266×10^6	9.5167×10^6	8.8812×10^6
Total lbs. of water[(c)] vapor used per hour	0.8811×10^6	0.9088×10^6	

TABLE 6-13 (cont'd.)

	Case One (scrubber)	Case Two (scrubber)	Case Three (low-sulfur coal)
Total volume of air[(d)] (cubic ft. per second)	40,568	47,156	47,112
Total volume of water vapor (cubic ft. per second)	6,228	7,240	
Total volume of exit gases at exit temperature (cubic ft. per second)	46,800	54,396	47,112

Note: The unit symbolized by "ug" is a microgram, i.e., 10^{-6} grams.

TABLE 6-14

SOURCES OF ACIDITY IN ACID PRECIPITATION COLLECTED IN ITHACA, NEW YORK, ON 11 JULY 1975 (31)

Component	Concentration in Precipitation (mg)	Contribution to	
		Free acidity at pH 3.84 (ueq)*	Total acidity in a titration to pH 9.0 (ueq)*
H_2CO_3	0.62	0	20
Clay	5	0	5
NH_4^+	0.53	0	29
Dissolved Al	0.050	0	5
Dissolved Fe	0.040	0	2
Dissolved Mn	0.005	0	0.1
Total Organic Acids	0.43	2	5.7
HNO_3	2.80	40	40
H_2SO_4	5.60	102	103
Total		144	210

* microequivalents per liter

SECTION 7

PLUME INTERACTION

7.1 INTRODUCTION

Cooling towers remove heat from condenser cooling water by evaporation and reject this heat to the air in the form of a hot and humid plume. The cooling tower plumes consist of water vapor saturated air and liquid water in the form of suspended droplets. The emissions from the stacks of fossil-fueled plants are primarily sulfur oxides and nitrogen oxides in addition to the usual constituents CO_2, N_2, O_2, particulates such as fly ash and trace elements. Vapor plumes from cooling towers are similar in most respects to smoke plumes from stacks, however, size differences are very great. Whereas smoke stacks are typically less than 100 ft in diameter, many modern cooling towers have diameters of several hundred feet.

The buoyancy of a plume depends on the mixing between the plume and its environment. For a given set of initial velocity and temperature conditions, a large plume will rise faster and reach a greater altitude. A vapor plume starts to cool immediately and results in a visible cloud of liquid droplets. This condensation will contribute to the buoyancy of the rising plume by releasing the latent heat of vaporization.

The total buoyancy of the cooling tower plume at a fossil-fired power plant is at least three or four times the buoyancy of the stack plume (1). Stacks are usually higher than adjacent cooling towers, but the total heat output from the stack gases is less than that from the cooling tower plumes. Consequently, the final plume rise from both sources is nearly the same, about 500 m. Thus, it is not surprising that the stack and cooling tower plumes are often observed to merge (1).

The presence of cooling towers (especially hyperbolic cooling towers which discharge their plumes at high altitude) at fossil-fuel power plants with stacks of heights similar to those of the towers engenders the distinct possibility that under the "right" meteorological conditions and relative orientation of the stack and the cooling towers the plumes will commingle. This interaction of large quantities of water with high concentrations of sulfur dioxide may reasonably be expected to lead to the formation of sulfurous and/or sulfuric acid droplets (2).

Generally, natural draft cooling towers are built in groups of two to four spaced 200 to 500 m apart. Mechanical draft towers are traditionally built in lines or "banks", in which 10 to 20 fan units are located in one 200-m long structure. Recently, some mechanical draft units have been arranged into doughnut-shaped structures, presumably to increase the plume rise from the group (1).

The separating distance between the boiler smoke stack and the cooling towers(s) is most often determined from other plant layout considerations; for example, the availability of land for the plant. When the sources such as the stack and the cooling towers are very close to each other, the plumes will at times combine or commingle. If the plumes are very far apart and the atmospheric conditions are stable, i.e., the winds are calm, the plumes will rise separately. Wind speed and direction play an important role in the plume merger. Thus, the wind rose at the plant location should be used to determine the relative location of the cooling towers with respect to the stack while establishing the plant arrangement and layout.

7.2 CATEGORIES OF PLUME INTERACTION

Sarma (3) classified the interaction between the plumes broadly into three different cases (Figure 7-1). In the first case, the tower plume containing suspended droplets of water mixes with the relatively hot stack plumes. This may result in a temporary defogging; but chemical reactions nevertheless take place, and the products will eventually be deposited as the mixed plume cools along its path. In the second case, the slightly cooled stack plume encounters the tower plume with its entrained liquid water, absorbing the oxides and resulting in a corrosive drizzle. In the third case, both plumes spread more or less in parallel and intersect at some distance away from their sources. This distance depends upon the wind velocity, atmospheric stability and the distance between the stack and the cooling tower.

7.3 MECHANISM OF INTERACTION

The mechanism of interaction between two neighboring plumes is not well understood (4). In general, it is not known if evaluation of plume effects near the tower will enhance plume performance predictions further downwind. Davis (5) modified a single buoyant jet model of Hirst to include effects of neighboring jet interaction for possible application to multiple-cell mechanical draft cooling towers. The merging processes of neighboring plumes within the zones of flow establishment and established flows of Hirst were used by Davis to define a merging zone explaining the asymmetry generated by interaction.

In this zone, it was assumed that the merging plumes make additive contributions both with respect to temperature and velocity. The merging zone continues until the profiles are smooth, i.e., the difference between neighboring temperature peaks and valleys is small. Recently, Kannberg (6) collected a large set of laboratory data for a two-dimensional plume source applicable to the analysis of Davis and was able to adjust the entrainment coefficients in the model to produce a very good fit with the data (Figure 7-2).

Although this phenomenon of interaction has been verified at plume level, the question of whether there is an attendant environmental impact, i.e., whether detectable quantities reach receptors at the ground, is still highly problematic (2).

When plumes merge, chemical reactions may lead to the production of undesirable substances such as sulfates. It is known that the conversion of SO_2 to sulfates by oxidation occurs more rapidly in a humid environment. However, no models of this phenomenon have yet been suggested. Current research efforts are studying chemical reactions in turbulent mixtures (1), but no one has developed a useful practical model. Donaldson and Hilst (7) pointed out that chemical reactions in inhomogeneously mixed fluids, such as a stack plume merging with a cooling tower plume, may proceed slower than reactions in a homogeneously mixed fluid. Studies by Thomson (8) in the Keystone plume may permit the development of practical models for this phenomenon (1).

The Chalk Point Cooling Tower project studied interactions between the cooling tower water vapor plume and the fossil power plant stack gas plume, especially the potential for the formation and the subsequent fate of sulfuric acid mist (2).

A model of the particulate distribution at the ground level due to interaction of the cooling tower plumes with stack plumes indicated that the rates of the chemical reactions are not sufficiently known to make useful or accurate predictions concerning the quantities of the various species. However, for purposes of this study, assuming that only the lumped principal reactions are of importance is justified because of the relatively short residence times before mixing. The concentration distribution, C, of these reactants in the stack plume can be expressed by means of the equation:

$$C(x,y,z) = Q/(\pi\sigma_{yx}\,\sigma_{zx}\,\bar{u})\ \exp\Big\{-\tfrac{1}{2}$$
$$\Big[(Y/\sigma_{yz})^2 + (z^2 + H^2)/\sigma_{zx}^2\Big]\Big\}\cosh\,(zx/\sigma_{zx}^2)$$

where Q is the intensity of the source, H the effective stack height, $\bar{u}$ the mean wind speed and the σ's are standard deviations from the Gaussian distribution.

The mixing zone height, Z_M, is approximately equal to that of the tower effective height. Thus if complete mixing of the plumes at the zone of interaction is assumed, the source strength, M, can be computed for the mixed plume. The effect of the energy release due to mixing and reactions is insufficient to influence the plume height. Therefore, the ground-level concentrations of the particulate aerosol distribution at any downwind distance can be computed by means of the simplified equation (3).

$$C(x,o,o) = M/(\pi\sigma_{yx}\,\sigma_{zx}\,\bar{u})\ \exp\Big\{(-\tfrac{1}{2})(Z_M/\sigma_{zx})^2\Big\}$$

This shows that the ground-level concentration (GLC) is dependent on the effective stack or tower height, wind speed, and intensity of the source or the source strength. However, the above equations do not have any term relating to the separation distance, L, between the cooling tower and the stack.

7.4 ACID PRECIPITATION ENHANCEMENT

Insufficient data is available for stack gas-cooling tower plume interactions. For the most part, existing literature provides unsophisticated explanations and non-quantitative descriptions. Three field studies included some quantitative analyses of plume merging cases (9,10,11). The rest of the literature deals with unsubstantiated hypothetical cases. The field studies are site specific in their analyses so that extrapolation to general circumstances is unreliable. For instance, the Chalk Point Study (9) analyzed the stack plume in which a wet scrubber was used whereas Dittenhoefer et al. (10) and Stockham (11) analyzed the stack plume at the Keystone plant which has no scrubber. These and other field studies are presented in detail in a later section.

A completely hypothetical case study was performed in an environmental licensing application in New York State by the Niagara Mohawk Power Corporation for the Lake Erie Generating Station (12). This study included a numerical model estimation of the chemical decay of SO_2 to SO_4; removal by precipitation scavenging was also predicted. The estimates of reaction rates, deposition rates and removal efficiencies were chosen on the basis of data in the literature although some judgement in the data interpretation was necessary. The data used to estimate rates and removal were obtained in laboratory experiements, making its applicability to atmospheric processes questionable. Because of these problems, only the worst case and annual coverage calculations are included. The results are presented in Tables 7-1 through 7-4.

Measurements of rainwater pH after passing through both the stack and cooling tower plumes are virtually non-existent. The role of precipitation scavenging of $SO_4^{=}$ is not obvious, possibly because of several factors: the small emission of SO_2 from a particular stack, the inefficient process of precipitation scavenging by droplet-particle collision, and the short time that the SO_2 can be absorbed by drops passing through the plume.

For example, Li and Landsberg (13) measured the rainwater pH after drops passed through both the stack and cooling tower plumes at Chalk Point for several rainfalls and obtained values from 3.4 to 4.6 during operation of the small stacks. The pH ranged between 4.0 to 4.8 for rainfall when the large stack (Unit 3) commenced operation. After the cooling tower became operational, pH frequency distribution shifted to a higher mode (4.0 to 4.5 instead of 3.5 to 4.0). Even though the SO_2 emissions were higher during the postoperations period, no explanation was offered for the observed increase in pH. Perhaps, the cooling tower plume diluted the acid already present. Apparently, sulfur dioxide oxidation was not a significant factor at the site.

Other studies considered only rainwater pH resulting from the stack plume interaction with the atmosphere. Dana et al. (14) found that sulfate concentration in rainwater due to the plume's presence did not appear to be significantly affected at downwind distances less than 10 kilometers (Section 7.5.5). The only measurable plume-related species collected were SO_2 and the H ion. The lowest rainfall pH under the plume measured 3.89. Rainfall rates varied from 0.8 to 2.4 mm/hr, and the average drop diameter was 0.03 to 0.1 cm. The H_2SO_4 scavenged by rain was calculated to be 178 lb/hr, or 45% of the amount emitted from the stack. Hence, the H_2SO_4 from SO_2 oxidation was minimal. The data of Hales et al.(15) also agreed with that of Dana et al. Although increases in SO_4 were observed in rain below the plume, the increase was not obvious. The H ion concentration distribution did reflect the plume location.

From a laboratory experiment, Esmen et al.(16) concluded that rainwater acidity through atmospheric scavenging accounted for the formation of very strong acids. This conclusion was based upon the kinetics of a reaction system containing micromolar quantities of SO_2, NH_3 and particulates in the presence of large volumes of water. However, the results of the Chalk Point study (17) contradicted the results of Dana et al.(14) and Hales et al.(15) by demonstrating that for post-operational periods the total SO_4 in precipitation was three times that for remote areas. The reasons for this dichotomy may be explained by two observations. One, limestone dust and fly ash buffer acids (18,19). Two, oxides of Fe, Ca, Na, Mg and Pb play an important role as catalysts in acid rain, but their role depends on their concentration and accessibility to SO_2.

Plume rise may be a function of buoyancy, and in some cases, the plume rise from the stack and cooling tower may coincide. Plume rise from a single stack where nearly all emissions are less than 20 microns has been described (20). Murphy (21) discussed the plume rise from a chimney row of single source momentumless plumes in a stable atmosphere. However, cooling tower plume rise is more complex due to the influence of latent heat release during condensation and the plume mass on plume rise. Latent heat provides additional buoyancy, although Hanna (1) contends that the difference is not sufficient to alter the rise significantly.

Part of the cooling tower plume with droplets whose mass is not large enough to be completely non-Gaussian may have a tendency to drift downward over distances. In effect, the plume centerline may have a tendency to fall over a limited distance after leaving the tower as the height distribution of the mass changes. For a single tower, numerous models exist to estimate the plume rise (1,22). The evaluation by Argonne indicates that some of these are fairly reliable (22). Unfortunately, this is not the case for multiple cell cooling tower plume rise models (R. A. Carhart, pers. comm.). Hanna and Gifford (23) theorized that the Briggs' formula for the multiple plume enhancement factor could be used for multiple cell cooling towers although they had no field evidence for confirmation.

In summary, additional sulfate production during visible merging of cooling tower and stack plumes, dispersion both from atmospheric turbulence and structural wake effects, plume rise from buoyant effects and meteorological conditions are processes useful in estimating the probability and quantity of acid drift-deposition. However, most of the work to date has been of a hypothetical nature. Field measurements are rare. Model generalizations are tenuous not only because of the few verified cases but also because of the different plant designs. Field data for stack gas-mechanical draft cooling tower plume merging are non-existent. Dispersion enhancement resulting from structural wake effects has not been extensively studied. In addition, wind tunnel studies indicate that small changes in structural design might have large impacts on the dispersion in a region out to about 10 building heights, thereby rendering general application of individual studies unreliable. No reliable process exists to determine the revision in atmospheric dispersion within a cooling tower structure wake and how the wake will affect plume rise. Buoyancy effects for plume rise prediction are somewhat better parameterized for various plant designs. At least the theoretical formulae for natural draft cooling tower plume rise due to buoyancy has been verified from field studies. Mechanical draft cooling tower plume rise formulae are not nearly as trustworthy.

Meteorological conditions conducive to stack gas-cooling tower plume merging have been established reasonably well in the literature,if it is assumed that an important criterion for acid drift-deposition is the commingling of the stack and a visible cooling tower plume. The longer than usual visible cooling tower plumes occur during light winds, high relative humidity (greater than 80 or 85%), low temperatures, and stable temperature lapse rates. The light winds and stable temperature lapse rates assure low dispersion rates both within and beyond the plant wake region. High relative humidity reduces the evaporation rate for the cooling tower plume so that plume length is enhanced. The cold temperature may be a reflection of a stable temperature lapse rate rather than an additional causative factor for visible cooling tower plume enhancement. However, the longer plumes do generally occur in winter rather than summer. Knowledge of meteorological conditions, cooling tower and stack plume rises and orientation of the stack and cooling tower permits the estimation of the frequency for stack gas-visible cooling tower plume merging. Orientation is significant because if the wind is perpendicular to the stack-cooling tower axis, dispersion will have an increased opportunity to mitigate both the droplet concentration of the cooling tower and the chemical concentration of the stack gas before merging, i.e., the plumes will merge further downwind.

7.5 FIELD STUDIES

Field studies have been conducted in several fossil-fired power stations, and plume merger and plume interaction have been investigated. This section examines the results of such studies at the following power plants: Keystone; Chalk Point; Ratcliffe and Rugeley (Straffordshire), U.K.; Mitchell & Kammer; Centralia; and, Amos. A complete summary is found in Table 7-8.

7.5.1 Keystone Station

The Keystone electrical power generating station is located near Sheluc, Pennsylvania. It is a mine-mouth, coal-fired plant with twin units, each with a capacity of 900 MWe, and a total capacity of 1800 MWe. Associated with each unit are a chimney stack, 244 m in height, and two natural draft, hyperbolic cooling towers each 99 m in height, 75.2 m diameter at the base. The cooling towers were designed and built by Research-Cottrell, operate with counter-current flow and have a total cooling capacity of 560,000 gpm. The tower design bases are: range(1) = 28°F, approach(2) = 18°F, wet bulb = 72°F, dry bulb = 86.5°F, and relative humidity = 50%. The center-to-center distances between the stack and the cooling towers are 830 ft and 1125 ft.

At the Keystone Plant, about 10,000 gpm of water were evaporated and 120 million Btu/min of heat released through the cooling towers when the station operated at 80-86% of its rated 1800-MWe capacity. The plume rose to about 200 m and travelled downwind about 200 m before evaporating.

Observations recorded at the Keystone plant can be summarized as follows:

1. When the ambient temperature was 25-30°F and the relative humidity was high (80%), the visual portion of the plume persisted for many miles and could be seen to merge with the stratus cloud cover. At higher ambient temperatures and lower relative humidities, the visible plume attained an altitude of 200 meters and a downwind distance of 100-200 meters.
2. In most instances, the cooling tower plume commingled with the stack plume. The most significant differences were the decrease in relative humidity from about 80% to 62% and a decrease in SO_2 concentration near the station from about 0.03 ppm to 0.017 ppm. No enhancement of the ground-level humidity was indicated as a result of the overhead plume.

The humid plumes from the cooling towers became mixed with the discharges from the power station stacks at downwind distances ranging from 200 to 1,000 meters. The plumes from the two sources remained mixed at downwind distances of 11,270 meters, the farthest point at which aerial traverses were made. While the cooling tower plume was visible normally 200 to 300 meters, the mixing was visually observed. Evaporation of the cooling tower plumes was confirmed by the profiles (Figure 7-3) of the humidity and sulfur dioxide obtained along the axis of the plume path (Figure 7-4). Cascade impactors mounted on a helicopter sampled droplets in the merged Keystone plumes. Results indicated that the number ratio of acid drops at pH = 4-5 to neutral drops at pH = 6-7 increased from .05 to 3.0 as relative humidity increased from 50% to 95%. Furthermore, the smallest drops had the highest acidity. Thomson (8) also reported that the smallest drops, i.e., those found in the last stage of the impactor, were associated with the highest acid concentrations.

The lack of correlation between the acid droplets and sulfur dioxide concentrations suggested that the plumes did not mix uniformly but may have just commingled. It was determined that acidity in the stack plume increased when the SO_2 and cooling tower plumes merged. Similar results, also verified on the Keystone plant, were reported by Thomson (8).

When relative humidity was low, stability near-neutral, and solar radiation intense, the production of new Aitken particles was the primary mechanism of

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(1) Temperature difference between hot water in and cold water out.

(2) Temperature difference between cold water out and inlet air wet bulb.

SO_2 oxidation. In the case of merger (100% relative humidity) between the stack plume and the cooling tower plume, the formation of sulfate on existing particles predominated over the formation of new particles. During cases with intermediate meteorological conditions, both processes were of equal importance.

Out of seven flights of a light aircraft making crosswind and longitudinal plume penetrations, in only one case, flight no. 4, did significant interaction between the stack plume and cooling tower plume occur. During this flight, the visible merged plume was detected out to 50 km downwind of the plant (over 110 min of plume travel time) and could be attributed to high atmospheric relative humidity, a stable lapse rate and low wind speed. Although similar conditions of stability and wind speed prevailed during flight no. 7, the slightly lower relative humidity and higher temperature caused the liquid plume to evaporate very near the towers and hence no visible merging was observed.

A significant growth of particle size was observed only in flight no. 4, due to absorption of SO_2 from the stack plume by liquid water of the cooling tower plume (see Table 7-5). Many of these droplets grew to sizes of 0.3 microns or greater. Thus, sulfate production accounted for much of this particle growth. The highest rate of particle growth (flight no. 4) occurred when the average plume temperature was at its lowest (1.6°F); lowest growth (flight no. 5) occurred during the case of highest temperature (62.1°F). Thus, temperature played a significant role in conversion of SO_2 to sulfate within the commingled power plant plumes. The conversion rate was of the order of 0.5% per hour. The sulfate particles collected in cases of low relative humidity and a non-merging plume were of significantly smaller size than those found during the merging plume case. The increase in modal sulfate particle diameter was about 0.3 to 0.5 microns (10).

The merged plumes produced an increase in the number of Aitken particles between 89 and 106 minutes downwind along with a very rapid increase in large particle concentrations (Figures 7-5 and 7-6). When the liquid plume disintegrated (visible plume disappeared), the large particle concentration decreased although it was almost one order of magnitude larger than the original stack value. It was believed that the chemical mechanisms caused a rapid growth of large particles (Figure 7-7). When the ratio of Aitken to large particles is nearly equal, then particle growth is comparable to particle generation as demonstrated in three of the flights (Figure 7-8).

From this data, it is apparent that the stack plume merging with the visible cooling tower plume does affect sulfate production. Although Dittenhoefer and dePena (10) were not able to measure the acidity of the droplets, they did make a projection for the conversion of SO_2 to H_2SO_4. Based on the assumption that particles are droplets of H_2SO_4 at 95% relative humidity and that the actual mass of solute contained within each size interval followed the Kohler curves for H_2SO_4, the conversion rate of SO_2 to H_2SO_4 was estimated to be approximately 0.5 percent/hr. This is a crude estimate, but the order of magnitude is believed to be correct.

Meteorological conditions which enhanced visible plume merging of the stack and cooling tower plumes to 50 kilometers were high relative humidity (95%), stable temperature lapse rate and light winds. Similar conditions for another flight existed, but no visible merging was observed; the relative humidity was slightly lower and the ambient temperature higher.

Effluents other than SO_2 and water from the stack and cooling tower may also mix (11). Mixing was verified by the presence of acid droplets in the visible cooling tower plume and by the humidity and sulfur dioxide profiles along the axis of the plumes after the cooling tower plume evaporation. In all instances, the humid cooling tower plumes commingled with the stack plumes. In the aircraft measurements, the droplets were classified in pH intervals (Figures 7-9 through 7-13). As the relative humidity increased so did the acid drop concentration. The SO_2 concentration had little effect on the acid concentration possibly because of non-uniform mixing. Even though the stack is 244 m and the cooling tower 99 m high, the buoyancy of the plumes rendered the height difference ineffective; the equilibrium height of both the stack and cooling tower plumes were approximately the same level. The plumes merged at distances from 200 to 1,000 m downwind. They remained merged until the end of the aircraft traverses at 11 km. The frequency of merging in this study concurred with observations at the AMOS plant by Kramer et al.(24) in which the merging of the stack and cooling tower plumes occurred 47 out of 54 times within a short distance of release. There was no measurement of chemicals after the merging in the latter study. It should be noted that all of these field studies have involved natural draft cooling towers. To date, stack-cooling tower plume merging field studies have not been performed on mechanical draft cooling towers.

7.5.2 Chalk Point Station

Chalk Point Station of the Potomac Electric Power Company (PEPCO) is located at the confluence of the Patuxent River and Swanson Creek in Prince Geroges County, Maryland, about 40 miles SE of Washington, D.C. Units 1 and 2 of the station are coal-fired, and base-loaded and employ once-through cooling. Units 3 and 4 are designed for peaking (cycling) services using oil as fuel and are rated at 660 MWe gross and 630 MWe net.

The Marley cooling towers for Units 3 and 4 are 400 ft (100 m) high and 283 ft (71 m) in diameter at the base (shell support). The crossflow cooling towers have a total cooling capability of 260,000 gpm. The design bases for the towers are: range = 30°F, approach = 12°F, wet bulb = 78°F, dry bulb = 93.5°F, and relative humidity = 50%. The diameter at the tower exit is 180 feet. The plant uses brackish water from the river with an average salt concentration of 7000 ppm. The boiler flue gases pass through a [illegible] venturi scrubber that uses brackish water. The stack plume, therefore, may contain NaCl, H_2SO_4 and SO_2 in addition to water.

Measurements in the plume interaction zone followed the test plan illustrated in Figure 7-14. Measurements of SO_2 and H_2SO_4 mist concentrations were made in the interaction zone. SO_2 concentrations were measured by a MRT Theta electro-chemical cell sensor. H_2SO_4 acid concentrations were measured by (a) chemical film sampler for droplets larger than 30 microns in diameter, and (b) the cascade impactor for droplets smaller than 30 microns. In both cases, the droplet collection surface was treated with quinine which reacts with H_2SO_4 to form Stabler 7 fluorescent quinine sulfate which was detected by ultraviolet light.

The boiler exhaust system includes a wet venturi scrubber that adds a significant amount of water to the boiler gas plume in the form of both droplets and vapor. Temperatures and concentrations of water and boiler plume constituents are much higher within the plume prior to dispersion. Reaction rates are, therefore, likely to be much higher in the exhaust system than at any time after emission from the stack. Therefore, it appears that reactions involving SO_2 and water would occur within the boiler duct and stack system prior to mixing of the stack gas plume with the cooling tower plume. Since the boiler plume already contains sufficient water for the chemical reactions to occur, the addition of more water from the cooling tower plume during mixing is likely to have only a small effect. There is insufficient experimental evidence to indicate any chemical reactions take place in the interaction zone of the stack gas and cooling tower plumes.

Baselines of ambient SO_2 concentrations beyond the edge of the plumes were less than 0.01 ppm, while typical smoke plumes ranged from 1 to 12 ppm. The highest concentrations of sulfuric acid were detected in the stack gas plume before mixing with the cooling tower plume (using the impactor sampler). This quantity, however, was near the threshold sensitivity of the analytical method (on the order of 150 ug/m^3). Because of plume diffusion and low reaction rates in the interaction zone, concentrations were lower in the interaction zone measurements.

These studies demonstrated the relationship of acid precipitation to effluents of dry (stack) and wet (cooling tower) plumes of the power plant. In general, the distribution of acidity in precipitation is governed by the source strength at the stacks and meteorological variables such as wind speed, wind direction, rainfall rate and amount.

Summer shower type of rain was analyzed for 1973 while Units 1 and 2 (once-through cooling; no towers) were the only source of SO_2. The pH of rain varied from 3.0 to 5.7. The hydrogen ion (H^+) concentration for each rain is very much wind dependent and falls off with distance from the maximum value near the power plant stacks. Before the cooling tower of Unit 3 was on, the pH for several rainfalls in the summer of 1974 ranged from 3.4 to 4.6. During cooling tower testing, when the boiler was burning at a low rate, the pH shifted to a range of 4.0 to 4.8. Several rainfall and pH readings were taken in 1975 when Unit 3 was used regularly and operated at a high burning rate. When the large stack (Unit 3) and cooling tower are on and the total amount of SO_2 increases, the rain becomes less acid close to the stacks. This suggests that the interaction of dry plumes with the wet cooling tower plumes has lowered the acidity in close proximity of the plant (13).

Chemical analysis shows that sulfate and nitrite are the main ingredients of acidity. Hence, the main source of low pH values were indeed attributable to SO_2 and NO_x from the combustion of coal (25).

Most of the acid formation occurred in the stack gas plume before mixing with the cooling tower plume, so that the wet Venturi scrubber provided significant H_2O in both droplet and vapor form within the exhaust gas duct and the stack thereby causing much higher reaction rates within the stack. The highest H_2SO_4 concentration was detected in the stack gas plume before mixing with the cooling tower plume. However, the exact concentration was not determined since it was below the measurable threshold value of the instrument.

The presence of stable visible plumes was observed during cold and high humidity conditions. Even under these conditions, however, the decrease in visibility was not considered to be a hazard to aircraft because of the limited distance over which it extended.

Thus, at Chalk Point interactions between the cooling tower plume and the stack gas plume were limited. The stack gas plume was saturated with water from combustion products and from a wet Venturi scrubber. Therefore, chemical reactions that require moisture occurred prior to mixing with the cooling tower plume, and the additional water supplied by the cooling tower plume had little effect.

Concentrations of sodium chloride and sulfuric acid were very low. Occasionally sulfuric acid was detected in the stack gas plume, but it was generally below the measurable threshold sensitivity (4 ug/m^3 for droplets larger than 30 microns and 150 ug/m^3 for smaller droplets).

7.5.3 Ratcliffe and Rugeley (Staffordshire, U.K.) Stations

The normal pH for the cooling water is 8.2, but the droplets collected under the cooling tower plumes varied between 2.4 and 7.3 (26). Lower pH values were observed when the plumes (before eliminator modification at Ratcliffe) had traveled several kilometers and the droplets were diluted by a factor of 3. The cooling tower droplets appeared to become acidic fairly quickly (some droplets collected at 400 m downwind in light winds had pH = 3.5), but Martin et al. (26) thought it more likely that on these occasions the SO_2 had come from low-level sources rather than from the stack plume.

Observations of natural rainfall under the stack plume at Rugeley in Straffordshire, which has one dry and several wet cooling towers, showed no significant difference in pH from that at rainfall stations in the area which were not under the plume (26).

7.5.4 Amos Station

The John E. Amos Plant, located 12 miles northwest of Charleston, West Virginia in the Kanawha River Valley, is coal-fired and has three units with a total generating capacity of 2900 MWe. Three Research-Cottrell natural draft cooling towers are in a line, 200 m apart. The two towers for Units 1 and 2 have a height of 132 m, top radius (R_o) of 29 m, initial vertical speed (W_o) of 4.6 m/s and are each capable of servicing a generator of 800 MWe. The third tower for Unit 3 has a height of 150 m, top radius of 40 m, initial vertical speed of 4.2 m/s and services the 1300 MWe turbine. There are two stacks each 274.3 m (900 feet) high, one services both Units 1 and 2 and the other Unit 3.

Kramer et al.(24) reported that in 47 of the 54 tests the plumes of the cooling towers and stacks merged, as observed visually, within a short distance of the release points. Their study did not include measurements of the chemical and physical nature of the droplets before and after the merging, but they contend that there is the possibility of interaction. Hanna (27) reported that vertical profiles of ambient temperature, dewpoint and wind speeds to heights of about 1500 m were obtained, and photographs of the plume were taken from a light aircraft. Merging of multiple plumes from the three cooling towers was observed. He proposed a plume and cloud growth model and made the following assumption to account for the plume merger: the plume radius grows to one-half of the distance between the towers, and then the cross sectional area of the model plume increases so that it is equal to the sum of the previous area of all the plumes.

7.5.5 Centralia Plant

Test results indicated that the SO_2 emission rate was 12,632 lb/hr and the H_2SO_4 emission rate was about 395 lb/hr (based on 2% conversion of SO_2 to SO_3 in the boiler) (14). The NO emission rate was not measured but presumed to be about 7,000 lb/hr. The mean pH beneath the plume centerline was 4.20; the minimum pH was 3.89.

The amount of H_2SO_4 scavenged up to 7 miles (11 km) was calculated to be 178 lb/hr or 45% of the amount emitted from the stack.

7.5.6 Cayuga and Milliken Stations

Measurements of acidity in precipitation have been recorded for the Northeastern U.S. (Table 7-6). Calculated emission rates for SO_2, H_2SO_4 and NO for the Cayuga and Milliken Stations at 100% capacity are given in Table 7-7.

Based on Centralia data, the lowest pH under the center line of the plume during rainfall at Cayuga and Milliken was predicted to be 3.5. This included a background contribution from the surrounding atmosphere equivalent to pH = 4.0.

7.6 MINIMIZING COOLING TOWER-STACK PLUME INTERACTIONS

7.6.1 Introduction

From the previous information presented, it is apparent that plume interaction is a complex phenomenon involving many factors. Natural parameters such as humidity, temperature, wind speed and direction, rate of precipitation and other meteorological factors are obviously not controllable. Therefore, to minimize the adverse impact on the environment, design parameters which contribute to the plume interaction must be controlled. These include: separation distance between stack and cooling tower, various SO_2 removal processes and the use of tall stacks.

The principal approach to control adverse plume interaction is likely to be SO_2 control. The major alternatives available for SO_2 control are given in Table 7-9 together with a partial listing of their characteristics. Use of naturally clean fuel, flue gas desulfurization (FGD), fuel pretreatment such as mechanical coal cleaning, coal liquefaction, coal gasification, and alternative coal combustion systems such as fluidized bed coal combustion and magnetohydrodynamics (MHD) are some controls for SO_2 generation. Table 7-10 presents a summary of various FGD processes now in use.

Fine particulates and nitrogen oxides are precursors that accelerate the formation of sulfate from SO_2. Fine particulate control may be necessary to prevent intrinsic health and welfare effects as well as the possible synergistic effects related to particulate sulfur oxide combination. Control of precursors such as catalytic particulates (vanadium, etc.) and photochemical oxidants without also restricting SO_2 emissions might be of limited value (28).

Other supplementary or intermittent control techniques include: use of very tall stacks, fuel switching, load shifting, and curtailment of operation when short-term or seasonal local meteorology forecasts indicate poor dispersion. Among these, much work has been done in the area of tall stacks and a detailed review of this topic will be presented.

Heights of the cooling tower and the stack must be sized so that the differences in plume buoyancy do not balance out. By making the stacks taller and the cooling towers shorter, the mixing of the stack and tower plumes can be avoided. Reliance on tall stacks and precursor control to reduce local SO_2 or sulfates could result in increased rainfall acidity. Recent evidence suggests that this would only aggravate the already serious acid rain problems discussed earlier (28).

7.6.2 Separation Distance Between Stack and Cooling Towers

Generally, natural-draft cooling towers are built in groups of two to four, with spacings of 200 to 500 m. Mechanical-draft towers are traditionally built in lines or "banks" in which 10 to 20 fan units are located in one 200-m long structure. Recently, some mechanical draft units have been arranged into doughnut-shaped structures, presumably to increase the plume rise from the group (1).

Briggs (29) assumed that the plume rise from multiple sources was enhanced by a factor E_n over that of a single source and recommended that:

$$E_n = \left(\frac{n + S}{1 + S}\right)^{1/3}$$

where: $$S = 6\left[\frac{(n - 1)s}{n^{1/3}\, h_1}\right]^{3/2}$$

E_n = plume rise enhancement factor
n = number of sources
s = center-to-center spacing between adjacent sources
h_1 = plume rise from one source

These formulas are for bent-over buoyant plumes and were tested against plume rise observations of TVA's Colbert, Shawnee and Widow's Creek Power Plant stacks. For calm conditions when buoyant vertical plumes are generated, a crude but simple method is suggested for predicting the height of the plume merger and subsequent behavior. This method is based on the geometry and velocity variations of a single buoyant plume. If n sources were clustered in an area of maximum center-to-center dimension D, the plumes will merge at a height $Z_m = 4D/(n)^{\frac{1}{2}}$.

The characteristics of the merged plume can be roughly predicted by assuming a single combined source at a virtual origin $Z = 1 - (n)^{\frac{1}{2}} Z_m$. If this equation is applied to clusters of sources, then (n - 1)s should be replaced by the maximum diameter of the clusters. This method was tested with data from multiple smoke stacks, with n as great as 9 (TVA), but has not yet been (October 1976) tested with data from cooling towers.

It is possible to calculate the spacing necessary to keep the enhancement factor below a certain value. When the number of sources is only two, i.e., n = 2, the enhancement factor is:

$$E_2 = 1 + \left[\frac{1}{1 + 1.5(\frac{s}{h_1})^{1.5}}\right]^{1/3}$$

For various $\frac{s}{h_1}$ ($\frac{\text{spacing}}{\text{plume rise}}$) ratios, the enhancement factor has been calculated as follows:

$\frac{s}{h_1}$	0.5	0.8	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
E_2	1.1825	1.402	1.1187	1.082	1.060	1.046	1.036	1.030	1.025	1.018

The data indicate that when spacing is about 1½ times the plume rise, the merged plume will rise 8.2% higher than the single plume.

As stated in a previous section, the meteorological conditions, plume rise from buoyant effects, and stack-cooling tower axis orientation to the wind are significant factors affecting plume commingling. Separation distance between the stack and cooling tower plumes increases the probability that the stack gas and visible cooling tower plume will not merge. Increased dispersion increases the evaporation rate of the cooling tower plume so that the visible plume is shorter. The stack-cooling tower orientation provides the same advantage for evaporation when the wind is perpendicular to the axis. Cost limitations restrict the distance at which the cooling tower can be spaced from the stack. Furthermore, there have been no studies explicitly evaluating the effectiveness of various separation distances. The value of separation distance has, therefore, not been experimentally evaluated for reduction of stack gas - visible cooling tower plume interaction and the resulting acid-drift-deposition.

A multi-faceted hypothetical evaluation including separation distance is feasible in order to crudely estimate the problem of acid-drift deposition. Evaluation of stack-cooling tower separation alone is not sufficient. This type of evaluation has been performed for the Niagara Mohawk Power Corporation as part of their license application for the Lake Erie Generating Station (12). This analysis evaluated the acid drift-deposition on the basis of chemical decomposition of SO_2 to SO_4 from available literature, estimated plume trajectories from the stack and cooling tower, the frequency of meteorological conditions expected to result in the maximum coexistence of the plumes at the same elevation, acid deposition predicted by a numerical model, and acid precipitation scavenging predicted by a model. The results were given in terms of the worst case and the annual average. The accuracy of such a study is questionable considering that the state-of-the-art for estimating structural wake effects is deficient, and deposition models predict results within a factor of two or more of observed results. More often, deposition models are reliable to one order of magnitude (22). Since this particular study has not been verified with field experiments, it may only provide a first order estimate.

To reduce the potential of stack gas - visible cooling tower plume merging, the following should be evaluated: the coincidence of high relative humidity, light winds, stable temperature lapse rates, wind direction parallel to the stack - cooling tower axis, and the design parameters of the stack and tower. Although merging frequency potential estimates based upon coincident meteorological conditions and design parameters are crude, it is reasonable to expect that the potential adverse effects from acid drift-deposition can be deduced by following this procedure. The stack and cooling tower design parameters, such as plume temperature, exit velocity, exit diameter, and flue gas and tower air flow rates, determine under what circumstances the stack and cooling tower plumes will rise to equivalent, or nearly equivalent, levels as a result of the buoyant effects. If the stack - cooling tower axis is oriented perpendicular to the wind under these coincident meteorological conditions, the merging probability is minimized. If the wind rose for such conditions is established from on-site data, then a first order estimate of the merging problem can be ascertained and the stack-tower axis can be oriented accordingly. In the same manner, the stack and cooling tower design parameters can possibly be selected to minimize coincident plume elevations.

In general, the separating distance between the boiler smoke stack and the cooling tower(s) is most often based on the availability of land for the plant. When effluent sources such as the stacks and the cooling towers are very close to each other, the plumes will combine or commingle. If they are very far apart, the plumes will rise separately. This is true if the atmospheric conditions are stable, i.e., the winds are calm. The wind speed and the wind direction will play an important role in the plume merger. Thus the wind rose at the plant location should be used in determining the relative location of the cooling towers with respect to the stack when establishing the plant arrangement and layout.

To establish guidelines on the separation distance between the stack and the cooling tower, their plume dimensions (plume rise, length, width or diameter at any downwind distance, the ground-level concentration, etc.) must be known. The interaction will be minimum when the plumes rise separately and do not merge. This occurs when the stack and the cooling tower are very far apart. There are advantages and disadvantages to increasing the tower spacing. An advantage is that the chances of cloud and rainstorm interaction are less if the plumes do not merge. A disadvantage is that the chances of high ground-level concentrations of fog drift and cooling water chemical additives are increased if the plumes do not merge but stay closer to the ground.

7.6.3 Use of Tall Stacks

Of many available methods for limiting ground-level pollutant concentrations, many times tall stacks are the simplest, most effective and least costly. However, a theoretically explicit, field validation of the soundness of using tall stacks is often hampered by the lack of comparable pre- and post-operational data.

In a study at the Alma Power Plant, appropriate air quality and meteorological measurements were made for several years before and after conversion from short to tall stacks (Table 7-13). Comparison of these data show that the tall stack reduced ambient levels of SO_2 by 50% to 95% in the vicinity of the plant (Table 7-12). This study also found that the use of a Turner-Briggs dispersion model in a valley situation gave fairly accurate and reliable estimates of air quality. The model was useful in designing the tall stack, assessing its impact, and locating air quality monitors (30).

Unlike the practice in many other portions of the United States, the plants in the Upper Ohio Valley were either originally built with tall stacks or were retrofitted with them when the benefits of doing so became apparent. Since stack height is a critical factor in the behavior of the discharged flue gases, all of the plants in the area are listed in Table 7-13 with their stack heights and the generating capacity associated with each stack. From this table, it is readily apparent that all of the major plants have stacks at least 500 ft high. The smaller plants with lower stacks, constituting less than 10% of the generating capacity, are fairly well dispersed so that no area is especially influenced (31).

A common method for achieving the standards of maximum ground-level concentration of SO_2 is to release the SO_2 through tall stacks so that it will be dispersed and reduced to an acceptable level of concentration prior to reaching the ground. This has been considered a rather short-sighted solution since it in no way reduces the amount of SO_2 emitted into the air (32). Tall stacks reduce ground-level concentration of SO_2, but increase sulfate aerosol formation by reducing losses of SO_2 and by increasing the atmospheric residence time, which results in increased SO_2 to sulfate conversion (33).

One problem related to stack height and plume merging problems, but which has not been studied except in wind tunnels, is the cooling tower wake effect. Bogh (34) and Kennedy _et al._ (35) determined that wake effects can be significant. However, the applicability of the wind tunnel study results to the field is questionable because of boundary effects at the plume walls (35). The main relevancy of this problem to plume merging is the effect of the aerodynamic and tower emission design upon the cooling tower plume rise. It is assumed that the stack is of sufficient height that no entrainment occurs as a result of any nearby structures. The Kennedy-Fordyne study of model rectangular mechanical draft cooling towers concluded that spacing does reduce the recirculation ratio. In addition, the orientation of the wind with respect to the tower affected the recirculation because of the entrainment around the tower ends. The value of zero for which the maximum recirculation ratio occurs appeared to generally decrease as the ratio of the exit velocity to wind speed decreased. For a wind blowing at 90° to the tower axis, the presence of a second tower at half a tower length downwind greatly increased the air entrainment. Increasing the mechanical draft cooling tower length means the tower height should be increased; otherwise, the entrainment around the end of the tower is enhanced. The trajectory and spreading of the plumes are affected far more by the ratio of exit velocity to wind speed than by buoyancy. In order to better anticipate plume rise and dispersion, these factors should be taken into consideration when designing mechanical draft cooling towers.

For natural draft cooling towers, the aerodynamic problems are not nearly as severe as for mechanical draft cooling towers since tower height determines the recirculation problem. Increasing the height noticeably reduces the entrainment, thereby minimizing the plume rise when compared with lower tower heights. The effects of tower structures are presently being modeled by Bogh (34) in order to provide a systematic process to evaluate the wake effects for various tower designs. Huber (38,39) modified the dispersion parameters to account for wake effects. Even though this wind tunnel model study was applied to building wake effects on stack effluents, some characteristics may be useful in anticipating tower structure effects, particularly for mechanical draft cooling towers. Huber found the ratio of the wake modified to the Pasquill-Gifford index decreased to nearly 1.0 at distances equal to 10 building heights. For 15 cases in a reported on-site study, there were no significant differences in the ratios between stable and unstable conditions. Simple mathematical representations of different parts of the flow field may provide a more refined and accurate approach to this problem (36). As yet, insufficient data exists to fully examine the wake effects (36).

Hatcher (37) performed a wind tunnel dispersion analysis in a building wake and reported that at some distance downwind, generally eight building heights for his structure, the rate of dispersion was independent on the release position and building orientation. Buildings enhanced only vertical dispersion for elevated releases. Minor changes in the building design can drastically alter the dispersion characteristics.

Although all of these dispersion studies estimating the wake effects are useful to characterize Gaussian flows, they do nothing to analyze the effects on large particle drift which is characterized by a ballistic trajectory. Only these droplets from a cooling tower which are less than 100 or 200 microns, depending upon the turbulence conditions, can be analyzed in a Gaussian regime. Unlike the tunnel studies by Bogh (34) and Kennedy et al.

(35) which attempt to analyze the effect of structural designs on plume rise and dispersion, studies by Huber (36,38,39) and Hatcher (37) are concerned more with dispersion.

In general, the introduction of tall smoke stacks and particulate removal devices have reduced the local "soot problem". Whether these procedures have altered (positively or negatively) the regional "acid problem" is an unanswered question (40). The use of a single stack to serve a power plant with multiple boilers has been analyzed by Hamburg (41) as a possible alternative to multiple tall stacks for pollution abatement. His analysis indicated that a single stack serving multiple boilers was more effective than much taller multiple stacks in reducing ground-level SO_2 concentrations. Furthermore, the single stack is considerably less costly to install and maintain than are multiple tall stacks and should be less objectionable to aviation and aesthetic sensitivities. Whether considered for new plants or retrofitting existing plants and whether or not scrubbers are used, the single stack appears to be a practical and economically attractive alternative for local pollution abatement (41).

Another alternative to lower ground-level air pollution concentrations is to reheat stack gases to higher exit temperatures. This produces a greater plume rise plume interaction. Thus, the effects of reheating are similar to that of a tall stack. Enviroplan (42) presented five alternate methods of stack gas reheating now in use. A steam injection method was utilized in a large number of demonstration projects.

A total system evaluation of several SO_2 control technology alternatives potentially available to the utility sector is presented in Table 7-14. The table clearly shows the difference in SO_2 emissions, energy efficiency, costs and timing when various control techniques are used.

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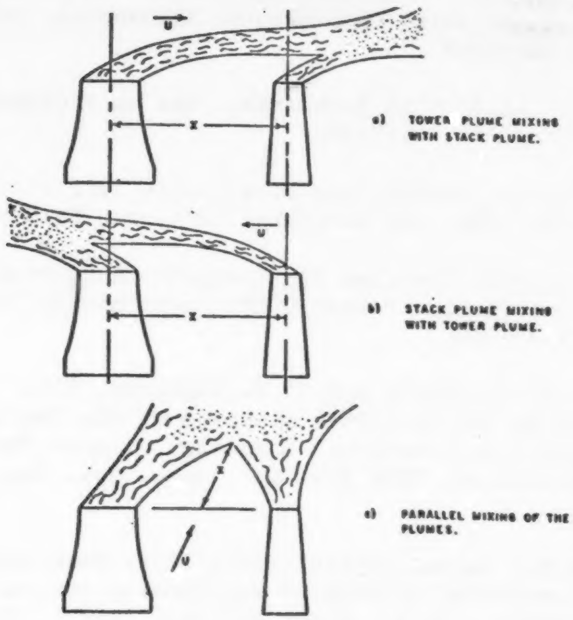
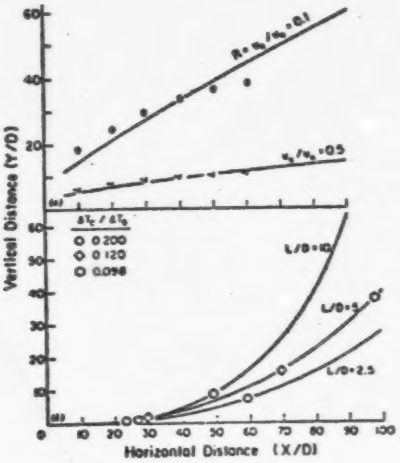


a) TOWER PLUME MIXING WITH STACK PLUME.

b) STACK PLUME MIXING WITH TOWER PLUME.

c) PARALLEL MIXING OF THE PLUMES.

Fig. 7-1 Plume interactions (3)



LEGEND

U_o = initial jet velocity
x, y, z co-ordinates
D = jet diameter
F = densimetric Froude number
R = U_c/U_o
L = jet spacing

Fig. 7-2 Comparison of predicted and measured plume trajectories
(a) with vertical discharge, R = -.01 and 0.5, F = 11, L/D = 2.5;
(b) with dilution showing effects of jet spacing L relation to diameter D (6).

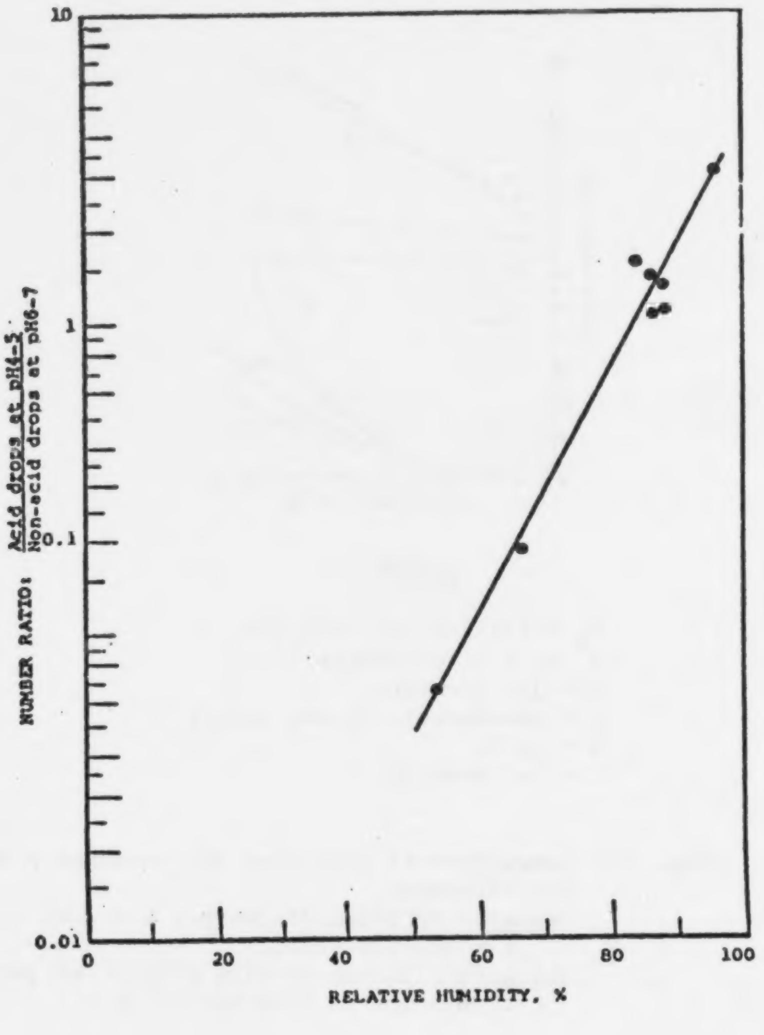


Fig. 7-3 Variation of acid drop concentration with humidity (4)

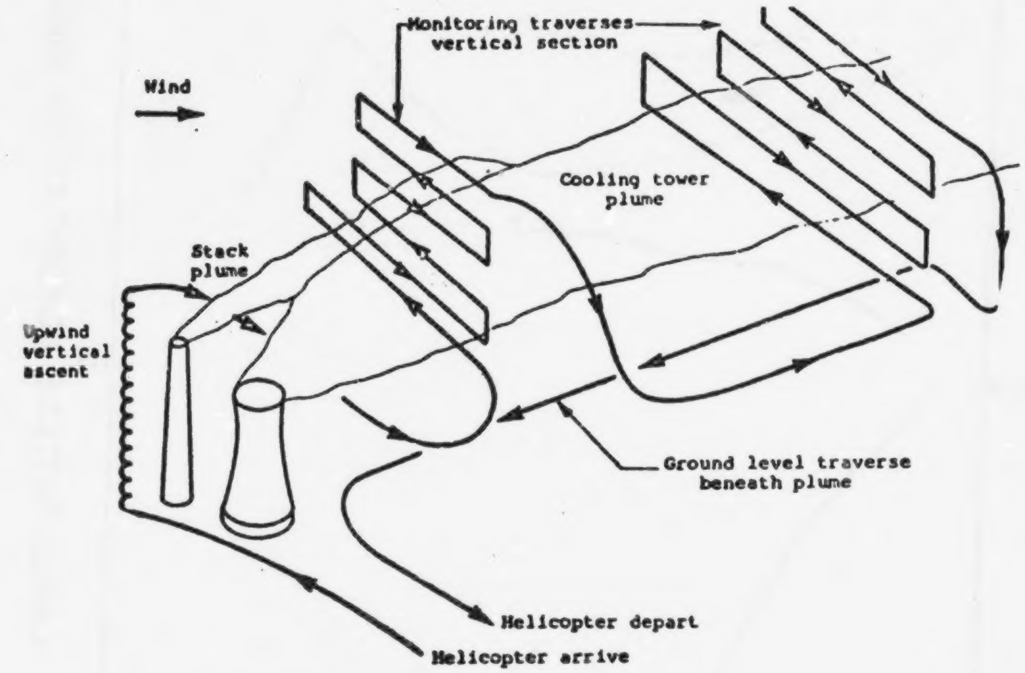


Fig. 7-4 Plume monitoring patterns (4)

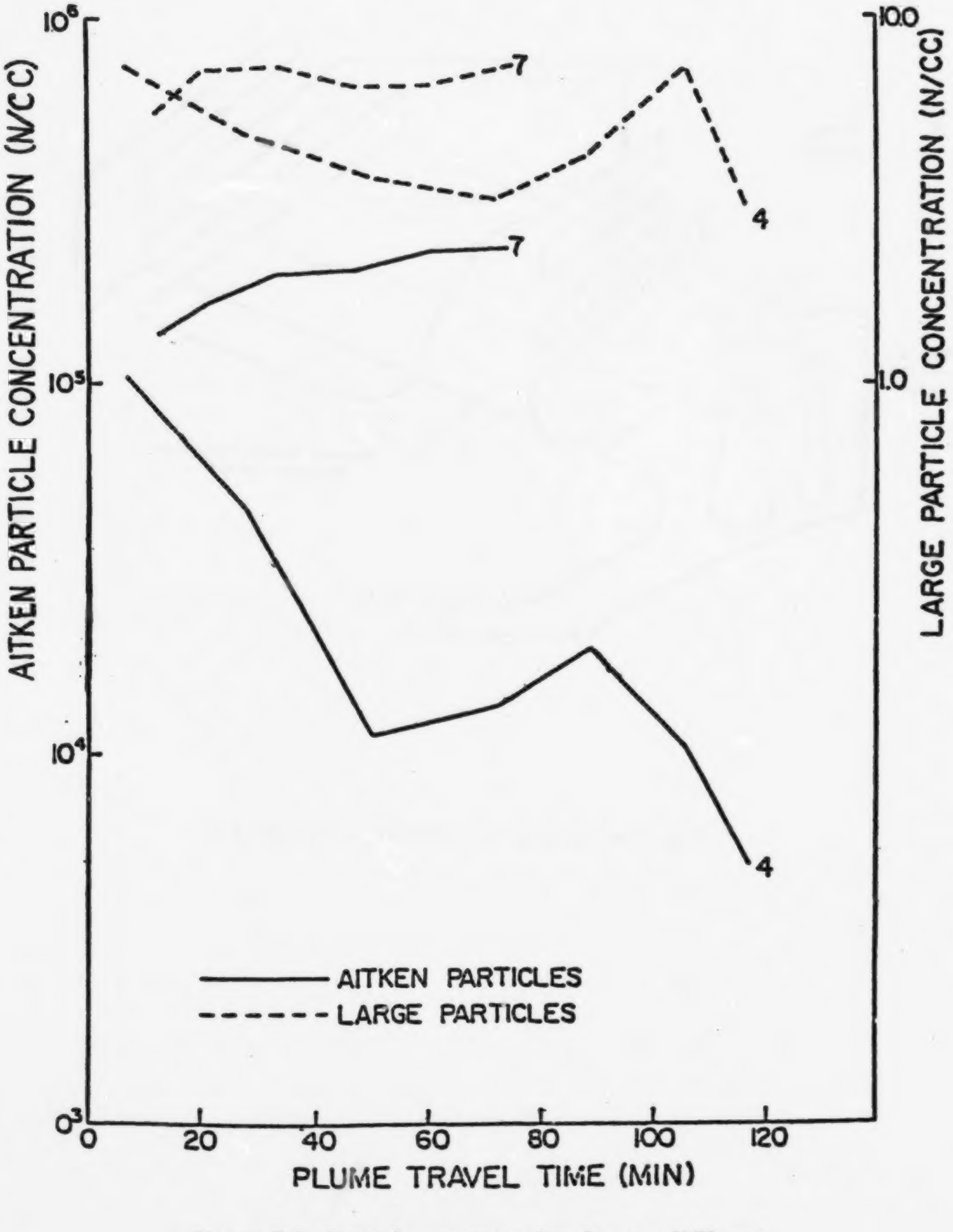


Figure 7-5 Particle concentration for two different flights at points along the plume path (10)

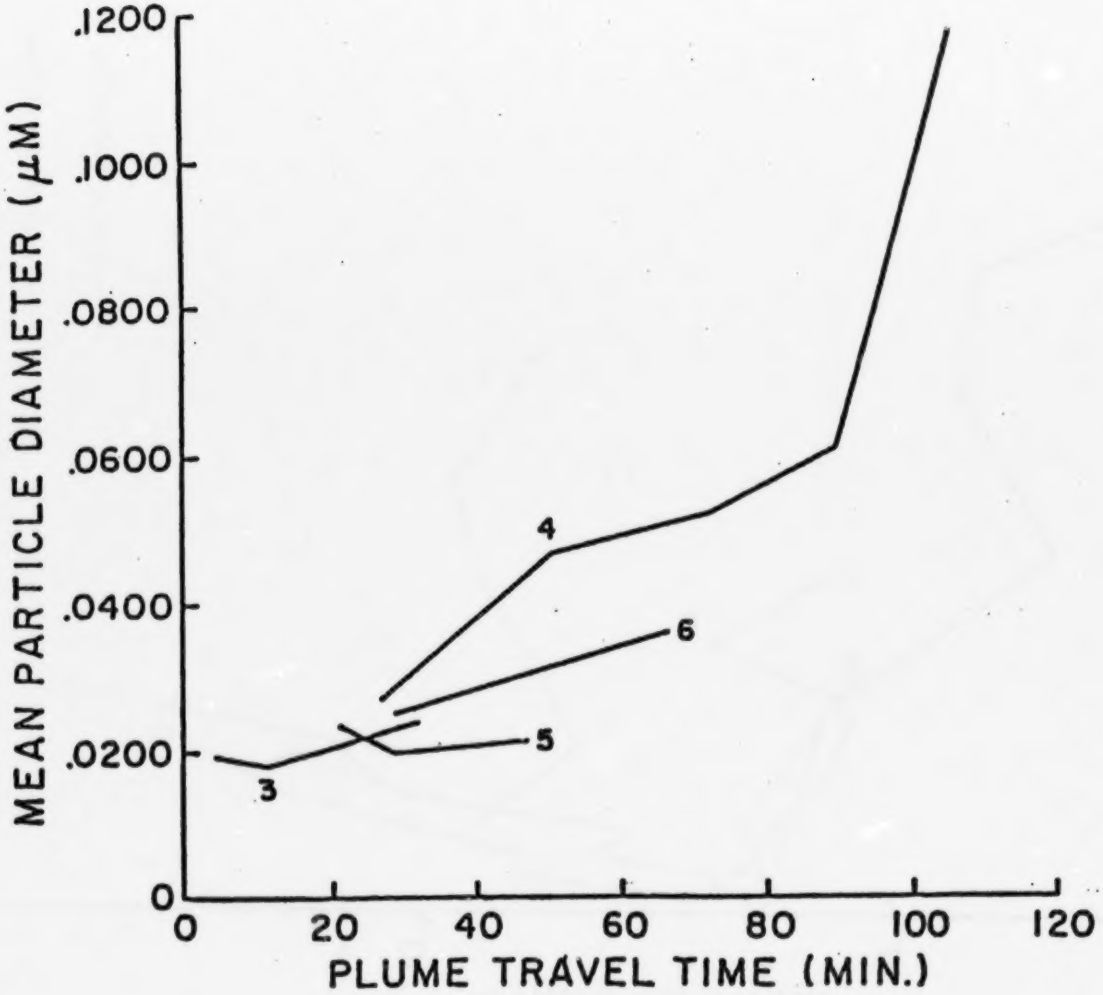


Figure 7-6 Particle growth observed during merged plume case (10)

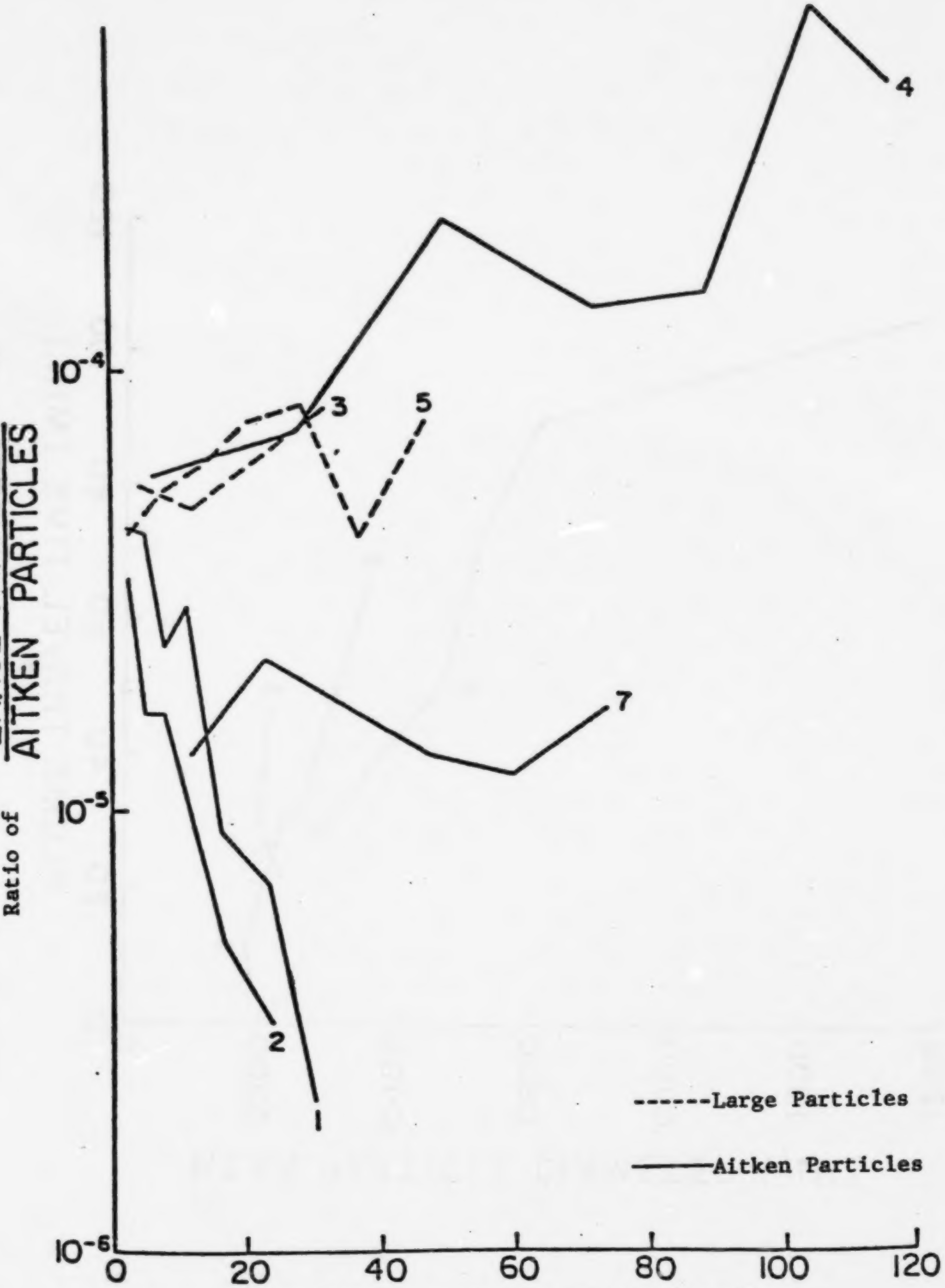


Fig. 7-7 Particle concentrations (10)

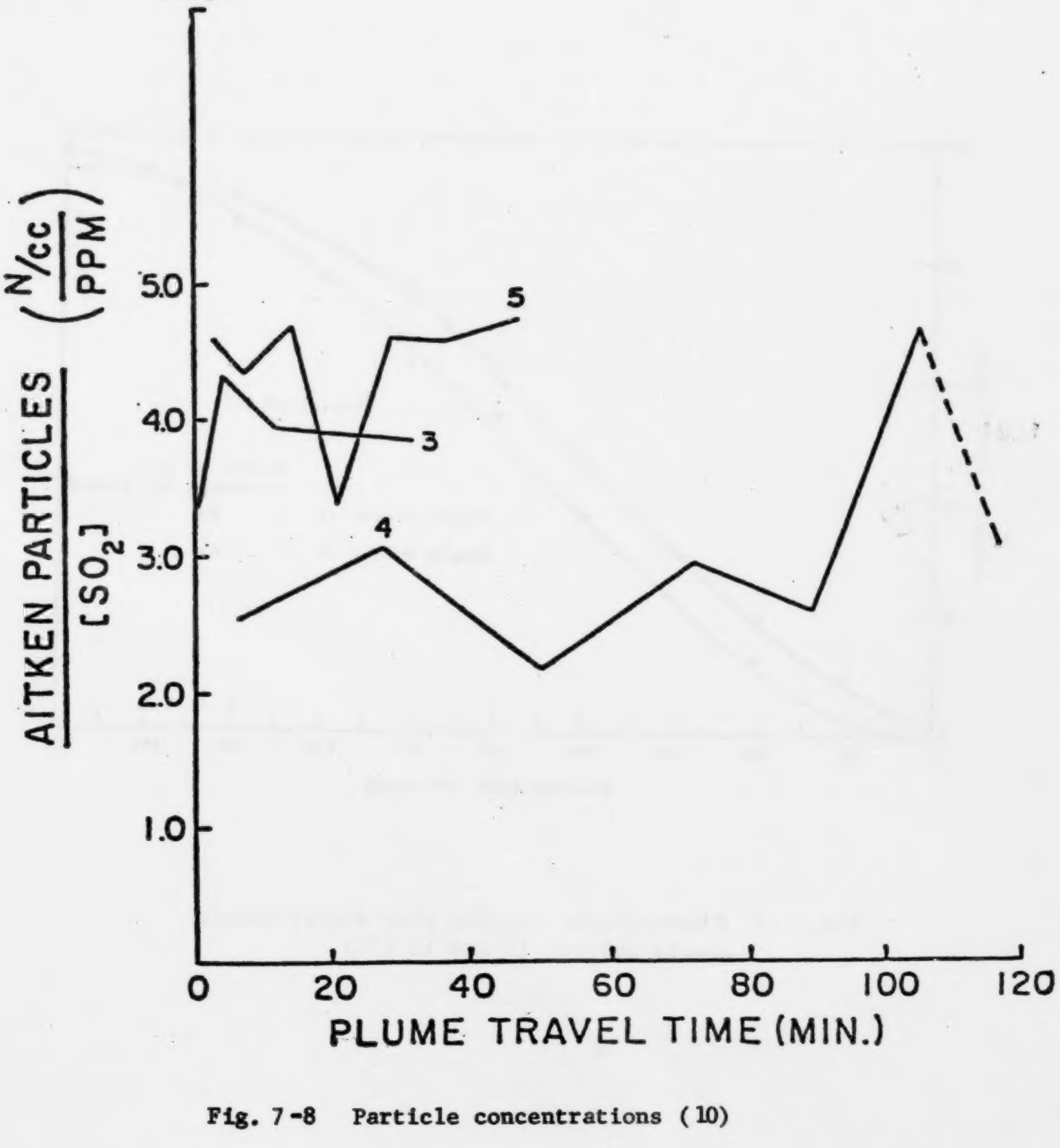


Fig. 7-8 Particle concentrations (10)

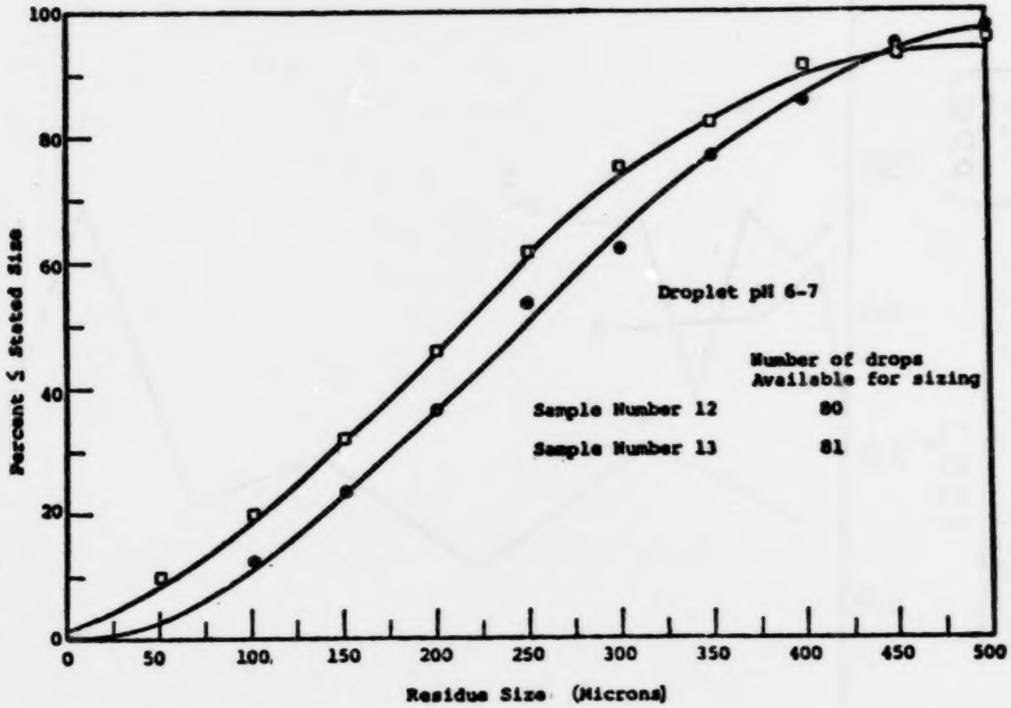


Fig. 7-9 Plume droplet residue size distributions sample numbers 12 and 13 (11)

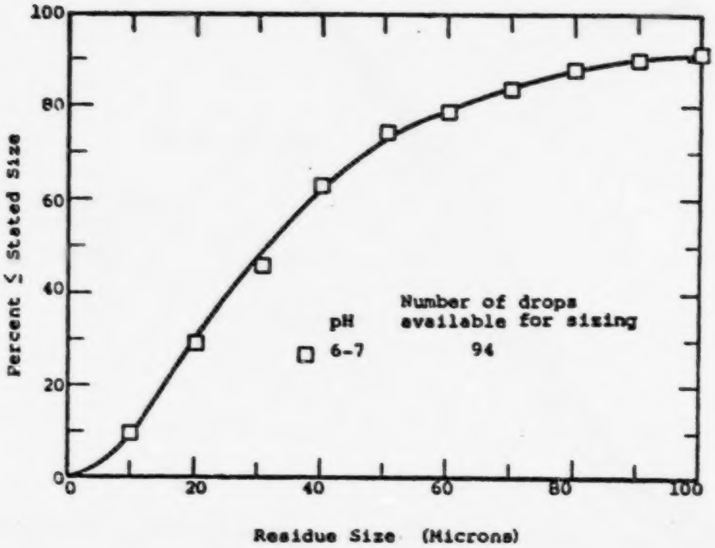


Fig. 7-10 Plume droplet residue size distribution sample number 6 (11)

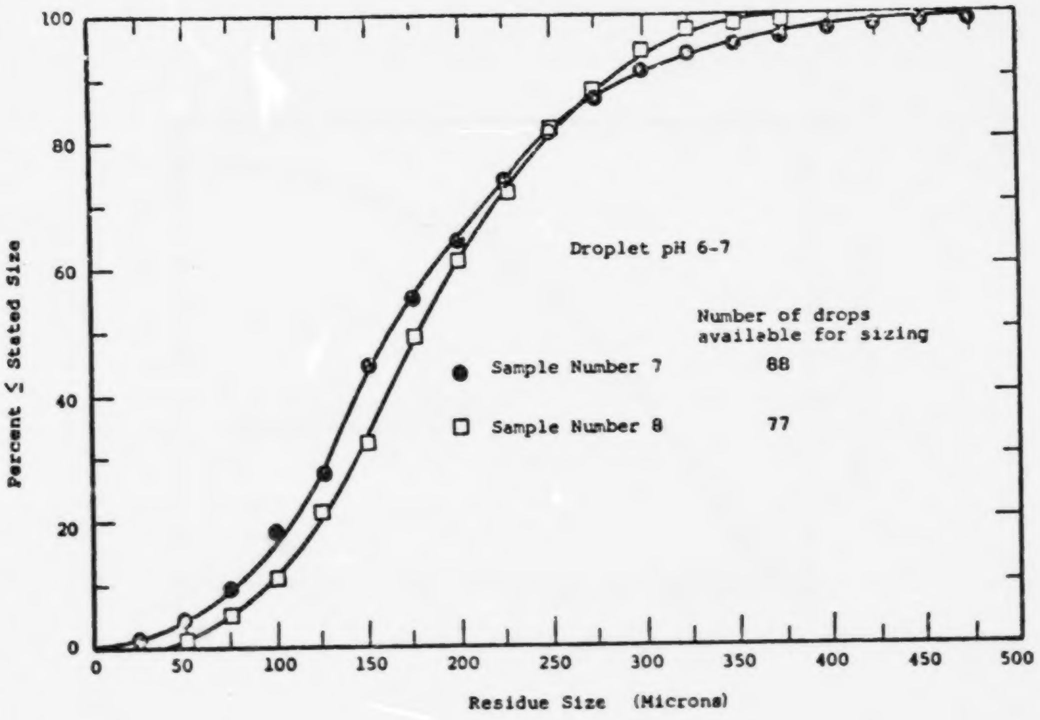


Fig. 7-11 Plume droplet residue size distribution sample numbers 7 and 8 (11)

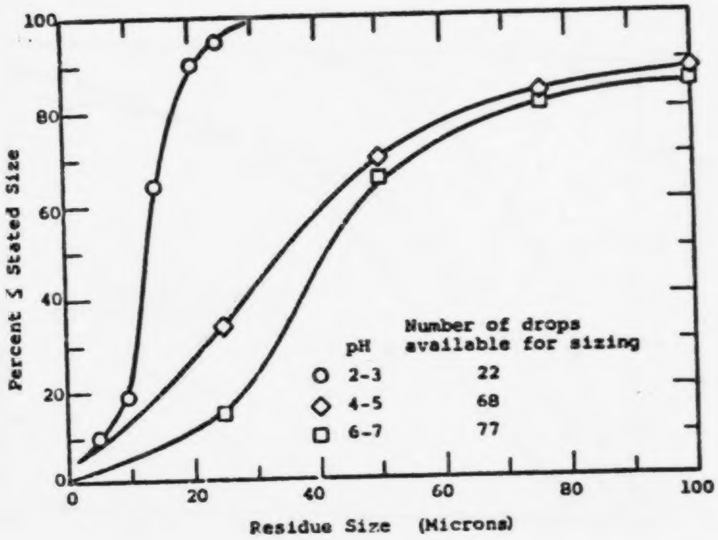


Fig. 7-12 Plume droplet residue size distribution sample number 1 (11)

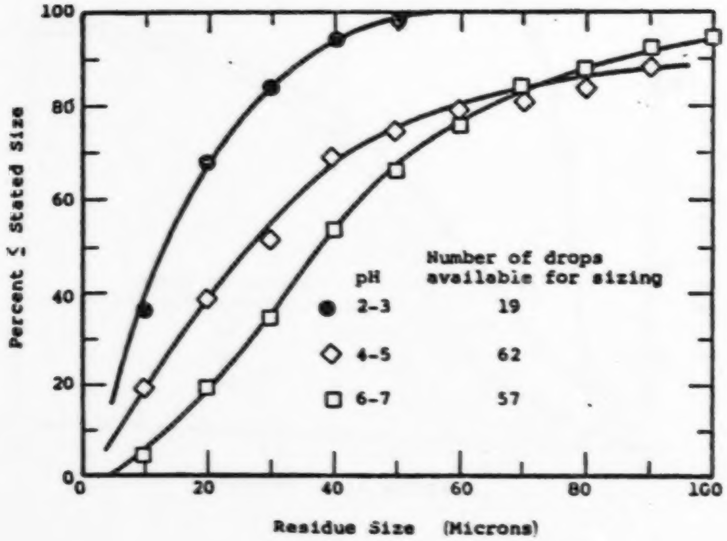
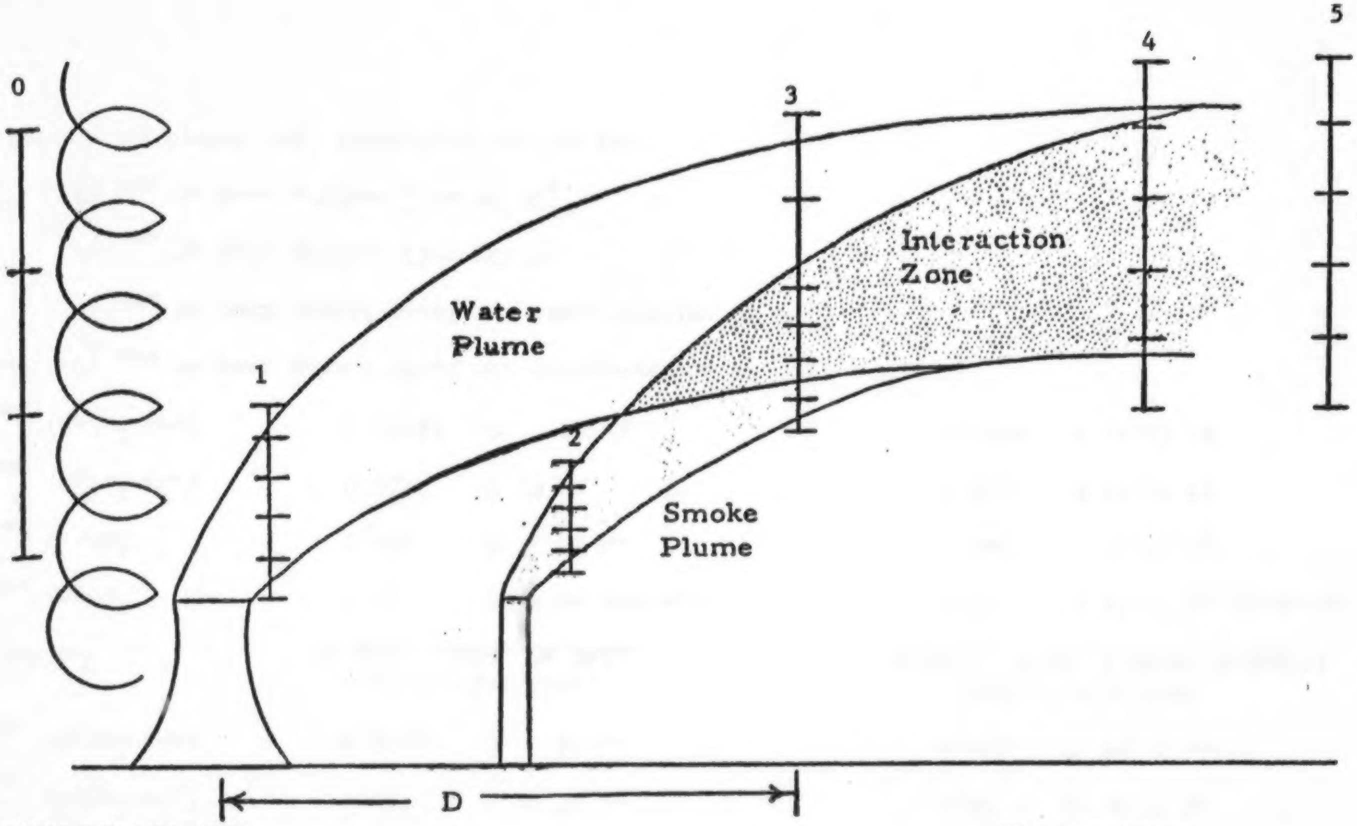


Fig. 7-13 Plume droplet residue size distribution sample number 3 (11)



DOWNWIND DISTANCE:

SAMPLING MODE:

Horizontal Traverse
Vertical Temperature Sounding

Sections

0. Upwind from source.
1. As close to water plume source as safety would permit
2. As close to smoke plume source as safety would permit
3. Slightly downwind from the beginning of interaction zone
4,5. Selected locations in the interaction zone based on the existing meteorological environment

Fig. 7-14 Plume interaction, test plan no. 3 (11)

TABLE 7-1

PREDICTED MAXIMUM GROUND-LEVEL AIR CONCENTRATIONS AND SURFACE DEPOSITION FLUXES OF SO_2 AND $SO_4^=$ DURING WORST CASE MERGING OF LAKE ERIE GENERATING STATION STACK AND COOLING TOWER PLUMES (12)

Case 1	Neutral Stability, 5.5 m/s Wind, No Rain		Neutral Stability 5.5 m/s Wind, 1 mm/hr Rainfall	
$C_{1\ max}$ (ug/m^3)	3.22	@ 18.25 km downwind	1.28	@ 8.5 km downwind
$C_{2\ max}$ (ug/m^3)	0.24	@ 25 km "	0.061	@ 11.5 km "
$F_{1\ max}$ (ug/m^2-sec)	0.065	@ 18.25 km "	0.23	@ 10.75 km "
$F_{2\ max}$ (ug/m^2-sec)	0.00048	@ 25 km "	0.011	@ 14.75 km "

Case 2	Neutral Stability, 15 m/s Wind, No Rain		Neutral Stability 15 m/s Wind, 1 mm/hr Rainfall	
$C_{1\ max}$ (ug/m^3)	2.03	@ 19 km downwind	1.15	@ 13.25 km downwind
$C_{2\ max}$ (ug/m^3)	0.093	@ 25 km "	0.045	@ 14.75 km "
$F_{1\ max}$ (ug/m^2-sec)	0.041	@ 19 km "	0.206	@ 16.25 km "
$F_{2\ max}$ (ug/m^2-sec)	0.00019	@ 25 km "	0.0078	@ 19.25 km "

Legend:
$C_{1\ max}$ is peak ground-level air concentration of SO_2.
$C_{2\ max}$ is peak ground-level air concentration of $SO_4^=$.
$F_{1\ max}$ is peak surface flux of SO_2.
$F_{2\ max}$ is peak surface flux of $SO_4^=$.

Note: The symbol "ug" represents micrograms.

TABLE 7-2

PREDICTED MAXIMUM GROUND-LEVEL AIR CONCENTRATION AND SURFACE DEPOSITION FLUXES OF SO_2 AND $SO_4^=$ FOR NON-MERGING CASES (12)

Case 3	Neutral Stability, 5.5 m/s Wind, No Rain	Neutral Stability 5.5 m/s Wind, 1 mm/hr Rainfall
$C_{1\ max}$ (ug/m^3)	3.65 @ 20.25 km downwind	1.87 @ 11.25 km downwind
$C_{2\ max}$ (ug/m^3)	0.193 @ 25 km "	0.072 @ 13.50 km "
$F_{1\ max}$ (ug/m^2-sec)	0.036 @ 20.25 km "	0.18 @ 14.5 km "
$F_{2\ max}$ (ug/m^2-sec)	0.00019 @ 25 km "	0.008 @ 18.25 km "

Case 4	Neutral Stability 15 m/s Wind, No Rain	Neutral Stability 15 m/s Wind, 1 mm/hr Rainfall
$C_{1\ max}$ (ug/m^3)	2.15 @ 19.75 km downwind	1.50 @ 15.0 km downwind
$C_{2\ max}$ (ug/m^3)	0.081 @ 23.5 km "	0.05 @ 16.0 km "
$F_{1\ max}$ (ug/m^2-sec)	0.022 @ 19.75 km "	0.143 @ 19.0 km "
$F_{2\ max}$ (ug/m^2/sec)	0.000081 @ 23.5 km "	0.0054 @ 21.25 km "

Legend: $C_{1\ max}$ is peak ground-level air concentration of SO_2.
$C_{2\ max}$ is peak ground-level air concentration of $SO_4^=$.
$F_{1\ max}$ is peak surface flux of SO_2.
$F_{2\ max}$ is peak surface flux of $SO_4^=$.

Note: The symbol "ug" represents micrograms.

TABLE 7-3

PREDICTED ANNUAL SURFACE DEPOSITION FLUXES OF SO_2 DURING PLUME MERGING (12)

Downwind Distance (km)	With Precipitation ($\mu g/m^2$-s)	Without Precipitation ($\mu g/m^2$-s)	Annual Deposition (mg/m^2) Pomfret (1)	Sheridan (2)
8	0.215	0.045	0.625	0.308
10	0.225	0.054	0.699	0.360
12	0.225	0.059	0.751	0.388
14	0.215	0.062	0.778	0.402
16	0.201	0.064	0.791	0.408
18	0.184	0.065	0.781	0.403
20	0.165	0.064	0.771	0.398
22	0.145	0.063	0.749	0.386
24	0.125	0.062	0.728	0.375

(1) One of the sites for Lake Erie Generating Station of Niagra Mohawk Power Corporation.

(2) Another site for Lake Erie Generating Station of Niagra Mohawk Power Corporation.

TABLE 7-4

PREDICTED ANNUAL SURFACE DEPOSITION FLUXES OF $SO_4^=$ DURING PLUME MERGING (12)

Downwind Distance (km)	With Precipitation ($\mu g/m^2$- s)	Without Precipitation ($\mu g/m^2$- s)	Annual Deposition (mg/m^2)*	
			Pomfret (1)	Sheridan (2)
14	10.69	0.36	9.71	5.05
16	10.66	0.39	10.04	5.20
18	10.36	0.42	10.27	5.28
20	9.83	0.44	10.16	5.24
22	9.15	0.46	9.93	5.15
24	8.34	0.47	9.71	4.97

*Multiply all rates by 10^{-3}.

(1) One of the sites for Lake Erie Generating Station of Niagra Mohawk Power Corporation.

(2) Another site of the Lake Erie Generating Station of Niagra Mohawk Power Corporation.

TABLE 7 -5

PARTICLE FREQUENCY (%) FOR FLIGHT 4 ON STAGE 3 OF THE IMPACTOR (10)

	Upwind	Downwind		
		12.2 Km	32.7 Km	49.0 Km
Non-Sulfate	88	91	88	30
Mixed*	4	7	6	16
Sulfate	8	2	6	54
*Volume fraction of sulfates within the mixed particles		75%	80%	87%

TABLE 7-6

SOURCES OF ACIDITY IN ACID PRECIPITATION[*] IN THE NORTHEASTERN UNITED STATES (43)

	Concentration in Precipitation (mg/l)[**]	Contribution to Free Acidity at pH = 4.19 (ueq/l)	Contribution to Total Acidity in a Titration to pH = 9.0 (ueq/l)
H_2CO_3	0.62	0	--[***]
Clay	5	0	5[+]
NH_4	0.195	0	11[++]
Al	0.036	0	4
Fe	0.040	0	2
Mn	0.005	0	0.1
RCOOH	1.1	5	17
HNO_3[++]	2.26	23[+++]	23
H_2SO_4[++]	2.80	36[+++]	37[ø]
	TOTAL	64	99

[*] Sample collected February 27, 1975 at Ithaca, New York.

[**] The total chemical composition is as follows: H, 65 ueq/l ; Ca, 7.4 ueq/l Mg, 1.6 ueq/l ; Na, 2.1 ueq/l ; NH_4, 10.8 ueq/l ; Al, 4.0 ueq/l ; Fe, 2.6 ueq/l ; Mn, 0.1 ueq/l ; SO_4, 58.2 ueq/l ; NO_3, 36.4 ueq/l ; Cl, 5.6 ueq/l ; PO_4, 0.2 ueq/l ; and dissociated organic acid, 5 ueq/l . The ion balance agrees within 10%, which is the equivalent of 0.04 pH units.

[***] H_2CO_3 was removed from system by N_2 purging. If the H_2CO_3 was not removed and the system was at equilibrium with the atmosphere, there would have been 5,000 ueq/l contribution to total acidity and no contribution to free acidity in a titration to pH = 9.

[+] This assumes that all of the particulate is montmorillonite; most likely the contribution to total acidity is an order of magnitude less than 5 ueq/l because of minerals other than montmorillonite with much lower exchange capacities.

Notes to Table 7-6, continued:

++This assumes that all of the NH_4^+ is converted to NH_3 which is subsequently removed by the N_2 purge. The most likely value is between 4 and 11 ueq/l .

+++The contribution to the free acidity is determined by a stoichiometric formation process in which a sea salt anionic component is subtracted from the total anions (Cogbill and Likens 1974).

ØAt pH=4.0, 1.5% of the total sulfate is present as HSO_4^-; thus total acidity for sulfate is greater than the free acidity.

NOTE: The symbol "ueq" represents microequivalents.

TABLE 7-7

CALCULATED EMISSION RATES OF SO_2, H_2SO_4 AND NO FOR CAYUGA AND MILLIKEN STATIONS AT 100% CAPACITY (45)

Substance	Plant	Emission Rate lb /10^6 Btu	 lb /hr
SO_2	Cayuga	1.176	9,353
	Milliken	3.724	10,999
H_2SO_4	Cayuga	0.037	293
	Milliken	0.116	316
NO	Cayuga	0.7	5,567
	Milliken	0.7[a]	1,898

[a] Assumed value might be as high as 1 lb/10^6 Btu.

TABLE 7-8

COMPARISONS OF COOLING TOWER-STACK INTERACTION STUDIES

Investigator	Plant	Results
Stockham (11)	Keystone	Acidity increased when stack plume merged with cooling tower plume. The number ratio of acid to neutral drops, pH=4-5 to pH=6-7, increased from 0.05 to 3.0 as RH increased from 50% to 95%. Decrease in RH from 80% to 62%, SO_2 concentration near to station decreased from .030 ppm to 0.017 ppm.
Dittenhoefer and de Pena (10)	Keystone	Droplets grew to 0.3 um* after 90 minutes of plume travel in interaction zone due to sulfate production. Highest rate of particle growth was at lower temperatures. The conversion rate of SO_2 to H_2SO_4 was 0.5% per hour.
Li and Landsberg (13)	Chalk Point	The rain close to the stacks was less acidic due to interaction. Plume interaction lowered the acidity of rain. pH of rain was in the range of 3.4 to 4.6 prior to cooling tower operation and shifted to 4.0 to 4.8 range with cooling towers in operation.
Woffinden (9)	Chalk Point	Concentration of H_2SO_4 acid was very low. Chemical reactions that require moisture have occurred prior to plume merger due to wet scrubbing, and the additional water supplied by cooling tower plumes has little effect.
Moore (44)	Ratcliffe,U.K.	pH of droplets collected under the cooling tower plumes varied between 2.4 and 7.3 after several km distance. The droplets became acidic fairly quickly. At 400 m, pH of droplets was 3.5.
Moore (44)	Rugeley, U.K.	No significant difference in pH occurred due to interaction.
Kramer (24)	Amos	In 47 of 54 tests, the plumes merged.
Dana (14)	Centralia	The mean pH beneath the plume centerline was 4.20, the lowest pH being 3.89. Tests indicated that H_2SO_4 emitted from the stack at 395 lb/hr and about 45% of this scavenged up to 7 km.

TABLE 7-8 (cont.)

Investigator	Plant	Results
MacKenzie (45)	Cayuga and Milliken	Predicted lowest pH under plume centerline was 3.5, with background at pH=4.0.

* The symbol "um" represents microns.

TABLE 7-9

SUMMARY OF CONTROL ALTERNATIVES FOR SO_2 (28)

Control Technique	Sulfur Removal Efficiency (3% S Base), %	Energy Penalty, %	Incremental Cost, mills/kWh	Timing	Annual Capacity, 10^6 tons Coal	Likely Applicability	Other Environmental Effects	Comments
Nonregenerable (lime/limestone) scrubbing (new plants)	90	3-7	3.0	1975-77	230 (1980)	All new utilities and large industrial boilers	Waste disposal problems	Operation load factor 80%, 1000 MW power plant
Nonregenerable scrubbing (existing plants)	90	3-7	4.4-6.1	1975-77	60 (1980)	Boilers - 100 MW - 20 yr age	Waste disposal problems	Operation load factor 60%, 300 MW power plant
Regenerable scrubbing (new plants)	80-95	3-7	3.4-7.0	1980	--	New utilities and large industrial boilers	Reduced waste disposal problems	Limited data on utilization and costs
Physical coal cleaning	30-50	3-10	0.6-1.6	1974-80	--	All coal combustors	Land, air, waste disposal at cleaning site	Cleaning costs $1.50/ton
Coal liquefaction (solvent refined cleaning)	75-85	20	10	1985	110	Existing and mine-mouth power plants, industrial boilers, small point sources	Sulfur and other emissions partially concentrated at central plants; increased mining necessary; unidentified air, water and solid waste problems	Economics of scale possible
Low-Btu Gas	80-98	10-40	6-16	1980-85 1980	13 200	New and large existing power plants		Energy penalty reduced by combined cycle application. Capital intensive.
Pipeline quality	98+	40	NA	1980 1985	29 50-100	Small and area sources		Minimal energy penalty if used to replace electric heat
Fluidized Bed	90+	Minimal	0-3	1985	150	New power plants and industrial boilers	Substantial reductions in NO_x emissions possible	Energy efficiency can be greater than conventional power plants
Refuse combustion	20	Minimal	Minimal	1985-90	50	Coal mix, 10-20 refuse	Benefits due to solid waste reduction	
Low sulfur western coals	75-85	Minimal	0-5.3	1980	250	Western and fringe eastern boilers	Increased particulate control	Energy penalty for transportation to eastern areas
SIP compliance coal (Eastern)	33-70	Minimal	1.0-3.0	1975	95	Eastern existing boilers		Cost for 1 S or less compared to 3 S coal
Desulfurized residual oil 0.3	85	--	2.0	1980-85	NA	Existing oil burners	Also removes Vanadium and other trace elements	

TABLE 7-10

SUMMARY DESCRIPTION OF MAJOR FLUE GAS DESULFURIZATION PROCESSES (28)

Process	Operating Principles	SO_2 Particulate Efficiency	Development Status
Lime/limestone scrubbing	Nonregenerable process/wet absorption in scrubber by slurry; insoluble sulfites and sulfates disposed of as waste	Up to 90 percent SO_2 removal/99 percent fly ash removal by most scrubbers	32 full-scale units (9829 MW) in operation or planned for start-up by 1977
Double alkali process	Nonregenerable process/wet absorption in scrubber; reactants and soluble; reaction products precipitated and removed from recycled reactant solution outside of scrubber; most common reactant, sodium sulfite	High efficiency 90 percent SO_2 removal/high particulate removal as above	Active area but no fullscale demonstration as yet; 2 units operating; G.M. installed a unit on a coal-fired boiler in February 1974; several sulfate removal schemes under study
Magnesium oxide scrubbing	Regenerable process/wet absorption by magnesium oxide slurry; fly ash removed prior to or after scrubbing; magnesium oxide regenerated by calcining with carbon; SO_2 by-product can be converted to sulfuric acid or sulfur	90 percent SO_2 removal/particulates removal as required by prescrubber	One full-scale unit on test at Boston Edison 150 MW oil-fired unit; Potomac power unit started in 1973 (coal-fired 100 MW)
Wellman-Lord	Regenerable process/sodium base scrubbing with sulfite to produce bisulfite; regeneration in an evaporative crystalizer. Sulfate formed either purged or removed by selective crystallization	90 percent SO_2 removal; particulate removal as above by pre-scrubber	Reliably operated (9000 hours) in Japan; full-scale demonstration scheduled at Northern Indiana Public Service coal-fired 115 MW boiler to start December 1975

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[a] Twenty-six units (13772 MW) under consideration have not yet selected a specific FGD process. Seven units (655 MW) are operating or planned using processes not summarized here.

TABLE 7-10 (cont'd)

Process	Application	Implementation	Advantages	Disadvantages
Lime/limestone scrubbing	Old or new power plant; coal- or oil-fired	An additional 21 units (10349 MW) planned for installation by 1980; 15 units (8-99 MW) considered for unspecified date; 4-5 years lead time needed for new plants; 3 years retrofit of old plants	Cheapest of existing processes; elimination of particulate control requirement	Waste and water pollution problems; reheat of scrubber exit gases needed; supply and handling of large volumes of reactant may be problems
Double alkali process	As above with potentially lower cost and greater ease of operation favoring some inroads into smaller plants	Research-Cottrell estimates $600 million a year market by 1979; a second generation lime/limestone system; lead times as above for power plants	Potentially cheaper and more reliable than lime/limestone system	Similar to above and all throwaway systems
Magnesium oxide scrubbing	Similar to lime/limestone but oil-fired boilers will not require particulate control upstream of scrubber	4 additional units (850 MW) planned or under consideration; lead times as for lime/limestone systems	May be more reliable than lime/limestone process; no known waste disposal problems; regeneration facility need not be located at utility	Cost of regeneration; marketing of sulfur products; reheat
Wellman-Lord	As above	5 additional units (1800 MW) planned by 1980; lead times same as for limestone systems	More reliable than lime/limestone system based on Japanese experience; simplicity of unit operations in regenerator; waste disposal problems reduced	Some bleed of solution to remove undesirable reaction products a source of water pollution, otherwise as above

TABLE 7-11

MEASURED MAXIMUM SO_2 CONCENTRATIONS (ug/m^3)(30)

	3-Hour Average	24-Hour Average	Annual Average
Before Modification			
Site 1	1457	540	70[a]
Site 2	2140	1517	57[a]
After Modification			
Site 1	658	131	17[b]
Site 2	458	79	9[c]
Site 3	626	157	15[b]
Site 4	487	73	10[b]
Site 5	589	142	16[b]
Federal & Wisconsin Standard	1300	365	80

NOTE: The symbol "ug" represents micrograms.

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[a] January-December 1973
[b] October 1974-September 1975
[c] May-October 1974

TABLE 7-12

FREQUENCY OF AMBIENT SO_2 CONCENTRATIONS EXCEEDING AIR QUALITY STANDARDS(30)

	Old Stacks			New Stack
	Number of Excesses	Average days per year	Percent of days per year	Number of Excesses
Site 1				
3-hr Average	1	0.7	0.2	0
24-hr Average	12	6.9	1.9	0
Site 2				
3-hr Average	13	8.8	2.4	0
24-hr Average	12	8.0	2.2	0

TABLE 7-13

STACK HEIGHTS AND ASSOCIATED GENERATING CAPACITY OF POWER PLANTS IN THE STUDY(31)

Power Plants	Stack Height, Ft	Generating Capacity
Steubenville-East Liverpool Area		
Sammis	500	376
	500	386
	850	980
	1,000	650
Toronto	650	172
Tidd	188	110
	188	120
Cardinal	825	600
	825	600
Windsor*	272	150
	272	150
Moundsville Area		
Burger	850	557
Kammer	600	450
	600	225
Mitchell	1,200	1,600
Southern Area		
Willow Island	138	60
	216	180
Sporn	600	600
	600	450
Kyger	535	430
	535	215
	535	430
Western Area		
Muskingum	825	840
	825	600
Philo	150	100
	150	100
	182	107

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*Plant was placed in cold reserve during 1973.

TABLE 7-14

PARTIAL SUMMARY OF POWER PLANT TECHNICAL CONTROL OPTIONS - REMOVAL AND ENERGY EFFICIENCY, COSTS AND TIMING (28)

		System						
Extraction	Transportation	Processing	Transportation	Utilization	SO_2 Emissions, lb/10^6 Btu	Overall System Efficiency	Overall Cost, Mills/kWhr	Estimated year of Application
East coal	Rail	Physical coal clean	None	Conv. boiler	2.02	0.324	10.0	Current
East coal	Rail	Physical coal clean	None	Conv. boiler lime scrubber	0.2	0.307	12.4	1975
East coal, S.M.	Rail	None	None	Conv. boiler MgO scrubber	0.50	0.349	11.5	1980
West coal, S.M.	Rail	None	None	Conv. boiler	1.65	0,369	11.5	Current
West coal, S.M.	Rail	None	None	Conv. boiler lime scrubber	0.16	0.349	13.3	1975
East coal, S.M.	Rail	Chemical coal clean	None	Conv. boiler	1.93	0.350	10.5	1980
East coal, S.M.	Rail	Coal liquefaction	None	Conv. boiler	0.7	0.276	13.2	1985
East coal, S.M.	Rail	Gasify, low Btu	None	Conv. boiler	0.017	0.329		1985
East coal, S.M.	Rail	Fluidized bed combustion	None	Combined cycle	0.07	0.378	10.8	1988
Oil well, onshore	Oil pipeline	Refinery domestic	Oil tanker	Conv. boiler	1.83	0.321	11.2	Current